FROM GENOMES TO ATOMS

THE BIG DOWN

Atomtech:

Technologies Converging at the Nano-scale

etc group

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SUMMARY: Atomtech on a Page

ISSUE: The key technologies of the past half-century—transistors, semiconductors, and genetic engineering—have all been about down—reducing size, materials and costs while increasing power. We are about to take a much bigger step down. Our capacity to manipulate matter is moving from genes to atoms. While civil society and governments focus on genetic modification, an impressive array of industrial enterprises is targeting a scientific revolution that could modify matter and transform every aspect of work and life. This report introduces a set of tools and techniques we call Atomtechnologies, which includes nanoparticles, nano biotechnology, nanofabrication and molecular manufacture. It also describes the coming convergence of biotechnology, information technologies, and cognitive sciences with nano-scale manipulation of matter as the unifying force. Section I (*What is Atomtech?*) introduces the technologies and Section III (*Will Atomtechnologies work?*) provides four criteria for measuring the commercial prospects.

IMPACT: Every form of work and enterprise will be affected. Section II (*Four [risky] steps down*) describes the present and future scope of the technology. The current global market for nano-scale technologies is estimated at around us$45 billion.[1] They already play an enabling role in biotechnology, pharmaceuticals, information and energy storage and in the booming materials industry. Nanofabricated circuitry is predicted to capture the silicon-based semiconductor market within the decade (global revenues in this sector alone will top us$300 billion by 2006). The technologies will move into conventional manufacture including everything from home appliances to clothing and food. By 2015, the world market for all steps of Atomtech will exceed us$1 trillion and the world will be faced with bionic organisms (Section II, *Atom and Eve*).[2] Though its impact will be felt first in the North, Atomtech—like biotech before it—will have early economic and environmental consequences for developing countries.

RISKS: A few scientists (and fewer governments) recognize that Atomtech poses both tremendous opportunities and horrendous social and environmental risks. Atomtech will allow industry to monopolize atomic-level manufacturing platforms that underpin all animate and inanimate matter. The present-day bulk production of materials and new forms of carbon with unknown and untested characteristics is a major concern. In the future, mass production of unique nanomaterials and self-replicating nano-machinery pose incalculable risks. Atomtech could also mean the creation and combination of new elements and the amplification of weapons of mass destruction. Section IV (*Who and where will it impact?*) continues earlier notes on risks and adds sectoral examples.

ACTORS: Public funding in the usa, Japan and Europe is in the range of us$2 billion per annum and rising sharply. Major corporations in every industrial sector are committed, from Bayer to Boeing, Motorola to Mitsubishi and from ibm to Exxon. Their in-house investment probably equals that of start-up enterprises. Total R&D spending worldwide in 2001 was about us$4 billion. Section V (*Who cares?*) examines the range of small and large companies, universities and governments working on the new technologies.

POLICIES: Most present-day Atomtech research does not directly manipulate living material—rather, the chemical elements vital to life—and has largely evaded regulatory scrutiny. Even the production and use of today's nano-scale materials could have breathtaking societal implications and the environmental impacts are unknown due to insufficient data and study. In the future, molecular manufacturing poses enormous environmental and social risks and must not proceed—even in the laboratory—in the absence of broad societal understanding and assessment. (Section VI offers policy recommendations.)

FORA: None. The impact of converging technologies at the nano-scale is either unknown or underestimated in intergovernmental fora. Since nano-scale technologies will be applied in all sectors, no agency is taking the lead. Governments and civil society organizations (csos) should establish an International Convention for the Evaluation of New Technologies (icent), including mechanisms to monitor technology development.

CONTEXT: Converging Technologies

This report describes and analyzes the convergence of nano-scale technologies and their potential societal impacts. Our goal is to translate complex scientific information and to catalyze widespread public debate. (New or specialized terms related to nano-scale technologies appear in bold in this document and are defined in the glossary—see "NanoGrammar" in Appendix B).

Industry and governments promise that the manipulation of matter on the scale of the **nanometer** (one-billionth of a meter) will deliver wondrous benefits. All matter—living and non-living—originates at the nano-scale. The impacts of technologies controlling this realm cannot be overestimated: control of nano-scale matter is the control of nature's elements (the **atoms** and **molecules** that are the building blocks of everything). Biotech (the manipulation of genes), **Informatics** (the electronic management of information), Cognitive Sciences (the exploration and manipulation of the mind) and Nanotech (the manipulation of elements) will converge to transform both living and non-living matter. When gmos (genetically modified organisms) meet Atomically Modified Matter, life and living will never be the same.

Today, public and private research at the nano-scale is evolving beneath the radar screen of civil society and government regulators. While society is mired in acrimonious—though vital—debates on the promises and perils of genetic modification, industrial enterprises are harnessing an Atomtechnology revolution that could modify all matter and transform every aspect of work and life. Understanding and oversight by civil society and governments is urgently needed or the products of nano-scale technologies will be rushed to market without transparent and democratic processes of review, assessment and regulation.

Traditionally, we have thought and manufactured on the macroscale (meters). Over the past 50 years, we have learned also to think and manufacture at the microscale (micrometers and smaller). We have just begun to turn our attention to the nano-scale, where the raw material of both science and commerce is the atom.

Atomtechnology refers to a spectrum of new techologies that operate at the nano-scale and below—that is, the manipulation of molecules, atoms and sub-atomic particles to create new products. By adopting the term *nanotechnology*, industry implies that the manipulation of matter will stop at the level of atoms and molecules—measured in nanometers. However, it would be naïve to assume that the nano-scale will be the final frontier. "Atomtech" better describes the technologies that aim to manipulate the fundamental building blocks of matter.

HISTORICAL CUE I

Technology: Impoverishing Improvements?

"He made a disgusted wave of his hand. 'Tis true, 'tis true. For though it can be said that a rising tide lifts all boats, a leaky skiff will scrape bottom no matter what the tide.'"

Gary Krist
Extravagance: A Novel

In his fictional contrasting of the London stockmarket of the 1690s and Wall Street in the 1990s, author Gary Krist shows that the two eras were driven by rapid technological transformations catapulted by greed and collusion between government and the Captains of Industry. While the rich led lives of unbelievable extravagance, London's poor and even New York's middle class became more marginalized.[3] Despite the passing of three hundred years, the lessons of history remain unlearned. Rising tides still swamp many boats.

INDUSTRIAL RENAISSANCE?

Historians usually peg the European Renaissance as being between 1450 and 1625 (or an era that roughly encompasses the lives of Leonardo da Vinci and Galileo). Some historians like John Gribbin are more precise. A period of science and discovery began, he contends, in 1453 when Gutenberg began printing the bible. Copernicus forced Europe to look "up" by publishing his treatise on the Revolution of the Celestial Spheres; and, Vesaluis urged Europe to look "down" with the publication of his revolutionary tome on the Fabric of the Human Body.[4] At a pace barely matched by today's Internet, printing presses spread across Europe within 25 years from Palermo to Oxford carrying the new thoughts and ideas to every nook and cranny of the continent. Copernicus changed our sense of ourselves in the universe but also pressed scholars to investigate the nature of matter itself. Vesaluis launched biology as a science–info, nano, bio!

Taxonomy of Converging Technologies

Biotechnology Encompassing a variety of techniques involving the use and manipulation of living organisms, biotech has become synonymous with genetic engineering (recombinant DNA technology), the process by which genes are altered and transferred artificially from one organism to another. Biotech focuses on the cell nucleus.

Nanotechnology Nanotechnology refers to the manipulation of living and non-living matter at the level of the nanometer (nm), one billionth of a meter. It is at this scale that quantum physics takes over from classical physics and the properties of elements change character in novel and unpredictable ways.

Cognitive Science Cognitive science focuses on how humans and other animals (as well as machines) acquire, represent and manipulate knowledge. Greater understanding of cognition enables the development of artificial intelligence where machines emulate mental processes. This discipline also includes cognitive neurosciences, enabling the exploration and manipulation of the mind, especially for "enhancement" of human performance.

Informatics Information technologies, including computing and communications, that allow scientists to capture, organize and analyze data.

Robotics A technology that focuses on building computer-directed machines capable of performing a variety of tasks.

Atomtechnologies All matter (living and non-living) is composed of nano-scale materials including atoms and molecules. Atomtechnologies refer to a spectrum of techniques involving the manipulation of molecules, atoms and sub-atomic particles to produce materials. Atomtech also involves the merging and manipulation of living and non-living matter to create new and/or hybrid elements and organisms. Atomtech's power will be fully realized with the integration of technologies that operate at the nano-scale, including biotechnology, informatics, robotics and cognitive science.

There are many ways to describe how these technologies will converge. The US government favors "NBIC"—nanotech, biotech, informatics and cognitive science. Bill Joy, the Chief Scientist at Sun Microsystems, has written provocatively about the implications of GNR—genetics, nanotechnology and robotics. Others point to "GRAIN"—genetics, robotics, artificial intelligence and nanotechnology. Whatever the acronym, the critical point about converging technologies is that they all meet at the bottom.

That the Renaissance was actually an industrial revolution has usually been ignored. "The main reason for productivity gains [during the Renaissance] was technological progress...," historian Carlo Cipolla insists, looking back on the explosion of wealth during that period.[5] The productivity of Italian weavers doubled and then tripled—even without the textile machinery that became the trademark of Britain's Industrial Revolution centuries later. Gutenberg's first printers churned out three hundred pages a day. By the end of the Renaissance, a printer could produce four times that amount. Between 1350 and 1550, English iron production rose seven or eightfold. Many of the Renaissance advances came in the areas of shipping and trade. Before Columbus, the crew-to-cargo ratio was one sailor for every five or six tons. The Dutch achieved a ratio of one man per ten tons by the end of the Renaissance.[6] Five hundred fifty years later: info, nano, and bio.

According to historian Kevin Phillips, "The Renaissance and the rise of capitalism, between roughly 1450 and 1625, hummed with technological and commercial innovations."[7] Venice became the hub of European commerce. The Northern Italian city-state so improved shipbuilding technology—pioneering assembly lines and interchangeable parts—that oceangoing vessels could be built in one day. Technology spurred the first modern era of Globalization. Between 1450 and 1625 trade in Europe grew by 600–800 percent. Not since the heydays of the Roman Empire had so much wealth been amassed so quickly.

But, as Phillips points out, while the rich lived lives of extravagance as a result of the new technologies, the cost of living increased desperately for the working classes.[8] "Peasants and tenant farmers staggered under rent increases that outran their crop receipts. Diets everywhere had less meat and grain and peasants spoke with envy of grandparents who had eaten elegantly from farming the same plot of land."[9] Inequities between rich and poor (especially with respect to food and shelter) grew greater than they had been for one thousand years.

DUTCH (TECH) TREAT: Technology, trade and capitalism united in the Low Countries (the British enviously called it "Dutch finance"[10]) to give Europe (*contd.*)

Generally, *nanotechology* refers to mechanical engineering on a molecular scale, but it is a slippery and ambiguous term. Sometimes it refers to today's applied nanotechnology, such as the use of **nanoparticles** in cosmetics or industrial coatings. Sometimes it refers to the longer-term goal of molecular manufacture—atomic engineering feats that are not yet possible. These are vastly different faces of a technology that have dramatically different implications for society. It is important to bear in mind that while some applications of Atomtech are market realities, others are in the early stages of development, and still others are dismissed as the aberrant visions of "fringe futurists." Based on recent history, etc Group believes it is distinctly "bad science" to dismiss any technological research that is so well-funded and involves so many diverse industrial actors.

Atomtechnology is trans-disciplinary. It borrows from physics, engineering, molecular biology and chemistry. Its real power lies in its ability to touch every sector of the world economy and its potential to re-define life itself. For example, genetic engineering as we know it today will be fundamentally changed and empowered by Atomtech. But Atomtech will eclipse genetic engineering because it involves *all* matter—both living and non-living.

The issue of ownership and control of this all-pervasive technology is paramount. Who will control the products and processes of Atomtech? Like the industrial revolutions that have preceded it, will we see a decline in the well being of poor people and increased disparity between rich and poor? Nano-scale manipulation in all its forms offers unprecedented potential for sweeping monopoly control of elements and processes that are fundamental to biological function and material resources.

The hype surrounding nano-scale technologies today is eerily reminiscent of the early promises of biotech. This time we're told that **nano** will eradicate poverty by providing material goods (pollution free!) to all the world's people, cure disease, reverse global warming, extend life spans and solve the energy crisis. Atomtech's present and future applications are potentially beneficial and socially appealing. But even Atomtech's biggest boosters warn that small wonders can mean colossal woes. Atomtech's unknowns—ranging from the health and environmental risks of nanoparticle contamination to **Gray Goo** and cyborgs, to the amplification of weapons of mass destruction—pose incalculable risks. While the potential to develop environmentally friendly and inexpensive products and processes is enormous, we do not know enough about the socio-economic, health or environmental implications of Atomtech—present or future.

its second industrial revolution. As did the Italians before them, Holland's inventors looked up (or out) and down–inventing both the telescope and the microscope for commercial use. Dutch technologies involving shipbuilding, fishing, and textiles, among others, dominated the 1600s.[11] The Low Countries had 6,000 ships in 1669–a commercial armada equal to that of the rest of Europe's.

IMPERIAL IMPOVERISHMENTS:

In the early 1700s, however, the technology torch was passed to a new industrial giant. The UK dominated the world at least from the mid-18th century to the late 19th century. Between 1808-1830 global trade rose by 30 percent. Between 1840 and 1870, world trade jumped fivefold with Britain controlling half of all manufacturing trade.[12] Uniquely, Britain's Industrial Revolution united power with portability. Steam power (through steam engines in factories and steam locomotives) made it possible for manufacturing to take place where ever most convenient. Industrialists could build close to labor markets or upwind from High Street.[13]

Once again, the enormous wealth generated by Britain's Industrial Revolution was far from universal. Between 1760 and 1845 the overall trend in working-class wages was downward. Even *The Economist* concedes that in the 19th century, "the initial enriching impact of the industrial revolution had given way to the Dickensian miseries of urban life."[14]

REPUBLICAN REVOLUTIONS:

By the end of the 19th century, industrial power shifted across the Atlantic to the United States. The advent of the railway and the telegraph in the mid-19th century spurred huge changes in US industry. With the coming of the automobile—followed by the airplane, radio, and a host of related technological innovations—US industrial dominance was definitive. The extravagances of the "Gay '90s" and the "Roaring '20s" are legendary. Less well remembered is that between 1920 and 1927 approximately 650,000 workers were added to the jobless roster. As many as 200,000 people per year were thrown out of work as a result of new technologies in the years immediately before the 1929 stock market crash.[15]

Another industrial revolution–one led by informatics and biotechnology—got underway in the final decades of the 20th century. Between 1980 and 2000, the share of total market capital held by high tech stocks in the USA

ETC Group's focus has always been on rural societies—especially in the South. The convergence of technologies at the nano-scale may seem a long way from rural communities in Africa, Asia or Latin America. It is not. More than twenty years ago, we warned that biotechnology would soon affect health and agriculture in developing countries. New technologies in the North also affect markets, imports and exports, labor requirements and production strategies. If the technologies are less than successful, they may be "dumped" in the Third World. If they are commercially successful, they may spillover into developing countries and/or radically transform local economies. With biotechnology, for example, the discovery that farmers' traditional maize varieties in Mexico have been contaminated with genetically modified DNA illustrates the potential health, environmental and trade impacts. The controversy over the shipment of US-grown genetically modified grains as humanitarian food aid to the South provides another example. While the immediate market interest in nano-scale technologies seems strongest in informatics and materials, much work is being done in nanobio-technology. Just as biotech came to dominate the life sciences over the past two decades, ETC Group believes that nano-scale convergence will become the operative strategy for corporate control of commercial food, agriculture and health in the 21st century.

ETC Evaluation

The point is not that technologies are bad (although certain technologies may be inherently destructive, centralizing or otherwise dis-empowering). Rather, the evaluation of powerful new technologies requires broad social discussion and preparation. Society must be informed and empowered to participate in decision-making about emerging technologies.

Warning

In 2002 breakthroughs in nanoscience are announced on a monthly basis and scientists are accomplishing feats thought impossible only a year earlier. Given the breathtaking pace of new developments in nanoscience, some information in this kit will likely be rendered out-of-date before it is published. Section VI lists resources where readers can find additional and updated information on Atomtech.

rose from 5 to 30 percent (before the collapse). But, while Corporate America brags about entrepreneurship and innovation, the development of semiconductors, computers, robotics, aero space technologies, and the Internet have either been instigated or heavily subsidized and protected by government. This has not only given us cell phones and GM crops but increasing inequity, unemployment and impoverishment in the United States and abroad.

TECHNOLOGY'S RISING TIDE: For at least 550 years, technological transformations have shaped world affairs. The importance of science and technology in the last century—and in the years ahead—cannot be exaggerated. Economists see technological advancement to be the rising tide allowing benefits and abundance to "trickle down" from those first enriched eventually to all. History suggests otherwise. From Europe's Renaissance to America's "IT" revolution, humanity has been marched through a succession of industrial revolutions that–in their early generations–have further dis-empowered and disabled marginal groups. Whether it is the technological transformation of Italy in the 15th and 16th centuries or of England in the 18th century—or the United States in the 20th century—each of these revolutions profoundly distorted social equity and politics. In each case the innovators were subsidized by the ruling class/government of the day. Each industrial transformation created extravagant wealth (whether for the Medici family or the Gates) and enormous poverty. The peasant farmers who were "out of the loop" in Renaissance Italy were defeated by the Price Revolution that accompanied the new technologies. Likewise, the miners and textile workers of Great Britain were caught in a price squeeze that expanded the ranks of the hungry. Nutrition was so imperiled that the average height of young military recruits in the UK, Sweden, Hungary, and the USA (where records are available) during their industrial revolutions declined substantially and did not return to pre-"revolutionary" levels for as much as a century.[16] As the Italians subsidized Leonardo da Vinci, the Dutch and British likewise subsidized their inventors and industrialists. The Americans made this collusion an art form. In every case, technologies have piggybacked on government in order to gain consumer acceptance and market monopoly. In every case, at least initially, the poor and marginalized have suffered.

SECTION I

1

The role of the infinitely small is infinitely large.

Louis Pasteur

WHAT IS ATOMTECH?

FROM GOLIATH TO DAVID Before an earthquake destroyed it in 227 bce, the Colossus of Rhodes, a bronze statue depicting the god Helios, straddled the city's harbor and towered 32 meters above the waves. It was considered one of the seven human-made wonders of the world. Lately, our appreciation of the wondrous has shrunk—from the very, very big to the very, very small—from "colossus" (Greek for "large") to "nanos" ("dwarf").

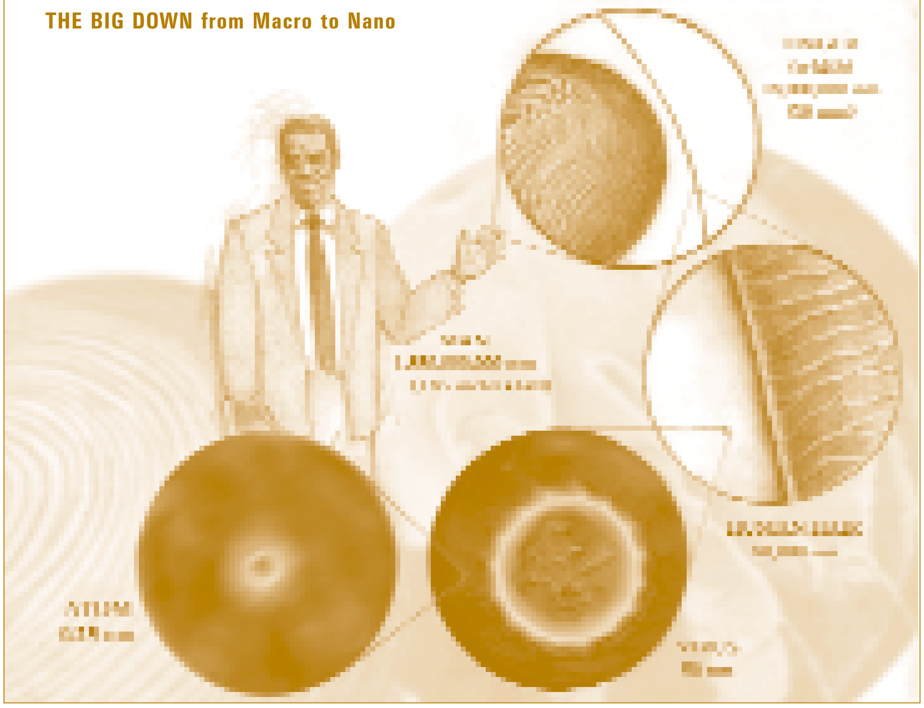
A SENSE OF SIZE *Atomtechnology* refers to a spectrum of new technologies that seek to manipulate atoms, molecules and sub-atomic particles to create new products. Industry prefers the term nanotechnology.[17]

"Nano" is a measurement not an object. Whereas the word *biotechnology* gives some idea of what material is being manipulated by means of human art—*bio* (i.e., life)—nanotechnology reveals only the size of the material being manipulated (a nanometer is one-billionth of a meter). Any thing on the nano-scale is invisible to the naked eye and to all save the most specialized instruments. Getting a sense of the nano-scale (up to 100 nanometers) is critical to understanding its importance.

"We have you surrounded and, by the way, that rock belongs to us!"

The biblical story of David and Goliath, wherein little David defeated mighty Goliath with a slingshot, teaches us that small can be more powerful than big. Today, mighty Goliath (industrial corporations) has learned his lesson and is exploiting the power of small to become mightier still, while little David (society) cannot even see his opponent.

THE BIG DOWN from Macro to Nano



Recipe for a Small Person

ELEMENT	FRACTION OF TOTAL BODY MASS
Oxygen	61%
Carbon	23%
Hydrogen	10%
Nitrogen	2.6%
Calcium	1.4%
Phosphorus	1.1%
Sulfur	0.2%
Potassium	0.2%
Sodium	0.14%
Chlorine	0.12%
Magnesium	0.027%
Silicon	260 ppm*
Iron	60 ppm
Fluorine	37 ppm
Zinc	33 ppm
Copper	1 ppm
Manganese	0.2 ppm
Tin	0.2 ppm
Iodine	0.2 ppm
Selenium	0.2 ppm
Nickel	0.2 ppm
Molybdenum	0.1 ppm
Vanadium	0.1 ppm
Chromium	0.03 ppm
Cobalt	0.02 ppm

* parts per million

To help you get a sense of size:

- Ten atoms of hydrogen lined up side-by-side stretch to one nanometer.
- If one hydrogen atom were enlarged to the size of this period (".") and if the letter next to it ("a") were equally magnified, the "a" would be 80 kilometers high.
- A dna molecule is about 2.5 nm wide (25 times bigger than a hydrogen atom). dna—the information-carrying substance that genetic engineers mix and match—is an assemblage of hydrogen, nitrogen, oxygen and carbon atoms.
- A red blood cell is about 5,000 nm in diameter, about one-twentieth the width of a human hair.
- The individual components of silicon transistors used in microelectronics span as little as 130 nanometers across, which means that Intel can fit 42 million of them onto its Pentium 4 chip.[18]
- A nanometer is 10^{-9} meters in length. 10^{-12} puts us in the realm of the nucleus of an atom; 10^{12} is on the scale of the entire solar system.

Medieval philosophers could only ponder this invisible realm, wondering how many angels could dance on the head of a pin. Without interfering with any eschatological calculations, scientists now know that 900 million nanoparticles can squeeze onto a pinhead.[19]

The Periodic Table

ATOMIC ALCHEMY: At the level of atoms and molecules, Atomtech's raw materials are the chemical elements of the **Periodic Table**, which are the stuff of everything else, including the genetic building blocks of life. The Periodic Table is a list of all known chemical elements, approximately 115 at present.[20] The symbols for each chemical element (usually the first letters in its name) are arranged in columns and rows, grouped according to chemical properties.

All matter, living and non-living, is made up of chemical elements. Since everything in the known Universe is constructed from hardly a hundred different building blocks, the infinite variety around us is the result of unique chemical "recipes" using a limited number of possible "ingredients." To function properly the human body requires 25 elements, but our bodies contain traces of all the elements that exist on earth.[21]

Hydrogen, for example, accounts for 88% of the atoms in the universe—it is in the sun, in water, in the earth's crust and in the human body. Carbon is a component of all matter that is living or was once living. Depending on variance in atmospheric conditions and temperature, carbon in its natural form can be graphite or diamond or coal. And many of us consume about 300 grams of carbon every day in the form of carbohydrates, fats and fiber.

Atomtechnologists seek to control the Periodic Table in the way that a painter controls a palette of pigments. The goal is to create new materials and modify existing ones.

CHARACTER LAWS: Size can change everything. At the nano-scale, elements can perform very differently than they do when they are on a larger scale. Stepping down from microtechnologies such as microelectronics and microprocessors to the nano-scale is a revolution all by itself. One micrometer is 1,000 times bigger than a nanometer. But the difference is greater than size. Below about 50 nm something that scientists call the "quantum size effect" kicks in: **quantum mechanics** take over from classical mechanics (classical mechanics governs the physical properties seen in both the

From Mendel to Mendeleyev:
The Austrian monk, Felix Mendel, published his treatise on genetic inheritance in 1865. Four years later Dmitri Mendeleyev, a Russian chemist, published his textbook including the first chart of the Periodic Table of Elements. Mendel described the regeneration of life; Mendeleyev charted the elements of life. These two pioneers of "bio" and "nano" never met–but their technologies have!

macro- and micro-worlds). With only a reduction of size and no change in substance, fundamental manufacturing characteristics such as electrical conductivity, colour, strength, melting point—the properties that we usually consider constant for a given material—can all change.

- A substance that is red when it is a meter wide may be green when its width is only a few nanometers (the gold of a wedding band looks yellow, for example; nanogold is red).
- Something that is soft and malleable on the macro-scale may be stronger than steel at the nano-scale.
- A single gram of a catalyst material (used to speed up chemical reactions) that is made of particles 10 nanometers in diameter is about 100 times more reactive than the same amount of the same material made of particles one micrometer in diameter.[22]
- A form of pure carbon at the nano-scale can be both a conductor and semi-conductor of electricity, whereas a large-scale form of pure carbon (e.g. diamond) is neither.

The changes in colour, strength, conductivity and reactivity that are observable at the nano-scale are attributed to the reduction in the size of the particles. By tailoring the structure of materials at the nano-scale, it is possible to engineer novel materials that have entirely new properties never before identified in nature.

The laminated layers of an abalone shell, as seen through a scanning electron microscope.

TOOLS FOR A TINY TECHNOLOGY: Before you can make or manipulate anything that takes advantage of quantum mechanics, you have to have the tools to see what's happening at the nano-scale. In 1959, physicist Richard Feynman delivered an address to the American Physical Society at the California Institute of Technology entitled "There's Plenty of Room at the Bottom." In that speech, the Nobel laureate (1965) laid the theoretical groundwork for nano-scale science (his audience was largely unmoved). Feynman explained that the biggest barrier to manipulating the nano-scale world was that we couldn't see it: the best electron microscope in 1959 was still about a hundred times too crude. Feynman concluded that "the problems of chemistry and biology can be greatly helped if our ability to see what we are doing, and to do things on an atomic level, is ultimately developed—a development which I think cannot be avoided."[24] And he put forth a challenge: "Is there no way to make the electron microscope more powerful?"

It took over twenty years to fully meet the challenge, but on August 10, 1982, US patent 4,343,993 issued to ibm for the invention of the Scanning Tunneling Microscope (stm), shedding fresh light on the atomic world.

QUANTUM CHARACTER CHANGE:

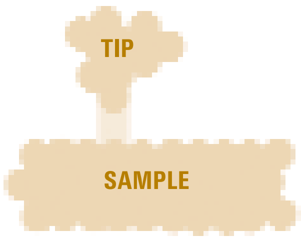
Chalk Talk & Pearls of Wisdom

The nano-scale invokes astonishing changes in the properties of common materials:

The abalone mollusk (the source of "mother-of-pearl"), for example, constructs an unbelievably durable shell by organizing calcium carbonate (the same substance as classroom chalk) into nano-structured bricks. For mortar, the abalone creates an elastic goo of protein and carbohydrate. If a crack starts on the outside of the shell, it has little chance of making it all the way through the thickness of the shell because the structure forces the crack to wind its way around the tiny bricks, diffusing the crack's energy. Aiding in damage control, the elastic-like mortar forms resilient nano-strings that try to force any separating bricks back together again. The quantum size effect changes characteristics without a change in the materials' chemical composition. The calcium carbonate that crumbles against the chalkboard becomes the impenetrable shell of the abalone.[23]

Scanning Probe Microscopies

Scanning Tunneling Microscope (STM)



Atomic Force Microscope (AFM)

Normally, we think of microscopes using lenses to magnify an object until it is big enough to be seen with an unaided eye, but an stm allows you to "see" indirectly, not by magnification. A fine needle-like tip that is electrically conductive is scanned just above the surface of an electrically-conductive sample. The distance between the tip and the sample is only a few Angstroms (a nanometer is 10 times bigger than an Angstrom) and that distance is controlled so that it remains constant. When a tiny voltage is applied, the rules of quantum mechanics allow electrons to jump, or "tunnel" across the space between tip and sample.[25] Though very small, this flow of electrons can easily be detected. As the tip moves along the surface of the sample, the tip's position is constantly adjusted to make sure the distance (and hence, the electrical current) remains constant. These adjustments trace the surface features of the sample. When the features are graphically displayed on a computer screen, we are able to "see" the individual atoms and molecules that make up the sample. Because it relies on electrical flow between tip and sample, the stm can only be used to examine materials that will conduct at least a small electric current. For their invention of the scanning tunneling microscope, Gerd Binnig and Heinrich Rohrer won the Nobel Prize in Physics in 1986.

A scanning tunneling microscope not only gives us a front-row seat in the atomic arena, it also can put us on the playing field. By increasing the voltage while the tip is positioned exactly over an atom, the atom can be made to stick to the tip; the atom can then be repositioned and when the voltage is lowered, the atom will be released from the tip in its new location.[26] In 1989, ibm researchers at the Almaden Research Center in San Jose, California (usa) picked up 35 xenon atoms (xenon is a chemically inert gaseous element) with the tip of an stm, one at a time, and arranged them on the surface of a nickel crystal. Not surprisingly, the scientists chose to spell out the letters I-B-M with their xenon atoms—forever associating Big Blue with small. The historic nano-logo spanned less than three nanometers.[27] Picking up and relocating atoms is not easy or cheap and it may not be the most profitable way to atomically-engineer products, but it is a demonstration of our growing ability to manipulate on the nano-scale.

Since the early 1980s, stms have evolved into **Atomic Force Microscopes** (afms) that are able to "see" a wider range of nano-scale samples. The process remains close to the one developed by Binnig and Rohrer, where a needle-like tip scans across a surface whose topography is "read" and then translated into a graphic image.[28] Using afms instead of stms, however, it is possible to look at samples that are not highly conductive, such as biological samples. Rather than maintaining a constant distance between electrically-conductive tip and sample, the tip of an afm is attached to the end of a highly sensitive cantilevered arm and actually touches the surface of the sample. The force of contact is very small. As with the stm, the tip scans the sample's surface to generate an image, but the afm records and measures the small upward and downward movements of the arm that are needed to maintain a constant force on the sample. The tip 'feels' the surface the way a finger might stroke a cheek. Because the touch must be delicate in order not to destroy the sample, several different methods have been developed, including one that gently taps the sample at unimaginably tiny intervals as it moves across its surface. Today, afms are the prerequisite tool that researchers use to observe and manipulate matter at the nano-scale; they cost anywhere from us$50,000–$1.5 million.[29]

Though Feynman may have been pleased by the developments in atomic-viewing in the first twenty years after his speech at Caltech, he would surely have been amazed by the progress in the second twenty years (Feynman died in 1988). The tools that enable nanoscientists to see and manipulate atoms are improving rapidly. In August 2002 ibm announced that it had developed a new electron microscope with resolving power less than the radius of a single hydrogen atom. The breakthrough will allow scientists to examine and correct atomic level defects in semiconducting material—a critical first step to making smaller, faster computer chips.[30]

IN THE THRALL OF THE SMALL: Getting small is not about shrinking machines simply to make more room on our desktops, although that will happen when more and more transistors can be packed onto smaller and smaller computer chips, for example. And it's not simply about our fascination with a realm outside of everyday human experience, analogous to the ancients' fascination with the colossal, though it may be partly about that. The real attraction of mastering the nano-realm is that it will expand our power to control other realms. The thrall of the small lies in the fact that the building blocks of all matter fundamental to sciences and industry originate at the nano-scale. Atomtech operates on the same scale as biomolecular processes, for example. If we can make machines on this scale we can use them to alter biological systems and we will also be able to put biomolecular processes to work as mechanical machines.

The power of Atomtech is that it will enable us to control and manipulate new realms, across many technological disciplines. Understanding the nano-scale is the first step.

It is also important to remember that the building blocks of matter—the elements of the Periodic Table—are not static. For more than 60 years, scientists in Europe and North America have been making their own contributions to the Periodic Table. Thus far, at least 17 elements have been created. (Some elements are in dispute, and, recently, the documentation of one element was proven to be bogus.) Even while scientists are constructing new elements, they are also learning more about sub-atomic particles and the unanticipated complexity of the structure of the atom. The "Big Down" does not stop with atoms themselves. In the years ahead, scientists will both make new elements and perhaps restructure and combine elements in ways we cannot imagine today. The possible socioeconomic and environmental implications of new forms of matter—materials never before seen on earth—are impossible to calculate.

In the following section, ETC Group introduces four stages of Atomtechnology, including both present-day and future applications and their potential impacts.

New to the Periodic Table of Elements: "Natural" Creations

Element
Year, Atomic Number
Who Made it and Where?

Technetium (Tc)
1937, 43
E. Segré and C. Perrier, University of Palermo Sicily, Italy

Francium (Fr)
1939, 87
M. Perey, Curie Institute, Paris

Neptunium (Np)
1940, 93
E. McMillan, P. Abelson, Berkeley, CA (USA)

Astatine (At)
1940, 85
D. Corson, K.R. Mackenzie, E. Segré, Berkeley, CA (USA)

Americium (Am)
1944, 95
G. Seaborg et al., University of Chicago (USA)

Curium (Cm)
1944, 96
G. Seaborg et al., Berkeley, CA (USA)

Berkelium (Bk)
1949, 97
S. Thompson, A. Ghiorso, G. Seaborg, Berkeley, CA (USA)

Californium (Cf)
1950, 98
S. Thompson, A. Ghiorso, G. Seaborg, K. Street Jr., Berkeley, CA (USA)

Einsteinium (Es)
1952, 99
A. Ghiorso et al., Berkeley, CA (USA); discovered by analysis of fall-out material from first thermonuclear explosion on Eniwetok atoll

Fermium (Fm)
1952, 100
A. Ghiorso et al., Berkeley, CA (USA); discovered by analysis of fall-out material from first thermonuclear explosion on Eniwetok atoll

Mendelevium (Md)
1955, 101
A. Ghiorso et al., Berkeley, CA (USA)

Nobelium (No)
1956, 102
Joint Institute for Nuclear Research (JINR), Dubna, Russia

Lawrencium (Lr)
1961, 103
A. Ghiorso et al., Berkeley, CA (USA)

Rutherfordium (Rf)
1969, 104
A. Ghiorso et al., Berkeley, CA (USA); probably first made in 1964 by JINR, Dubna, Russia

Dubnium (Db)
1967, 105
JINR, Dubna, Russia

Seaborgian (Sg)
1974, 106
A. Ghiorso et al., Berkeley, CA (USA)

Bohrium (Bh)
1981, 107
Gesellschaft für Schwerionenforschung (GSI, Laboratory for Heavy Ion Research), Darmstadt, Germany; probably first made in 1976 at JINR, Dubna, Russia

Meitnerium (Mt)
1982, 109
GSI, Darmstadt, Germany

Hassium (Hs)
1984, 108
GSI, Darmstadt, Germany

Ununnilium (Uun)
1994, 110
GSI, Darmstadt, Germany

Unununium (Uuu)
1994, 111
GSI, Darmstadt, Germany

Ununbiium (Uub)
1996, 112
GSI, Darmstadt, Germany

Ununquadium (Uuq)
1999, 114
JINR, Dubna, Russia (in collaboration with Los Alamos National Laboratory, New Mexico [USA])

Source: John Emsley, Nature's Building Blocks: An A-Z Guided to the Elements, 2002 (first pub. 2001)

Stepping Down: Some Major Milestones in Atomtech

1959 Nobel Prize-winning physicist Richard Feynman gives his now-famous speech, "There's Plenty of Room at the Bottom," describing the future possibility of atomic engineering.

1964 Glenn Seaborg, Nobel Prize Laureate for Chemistry, wins two US patents on elements he discovered–Americium #95 and Curium #96–a little known milestone that sets a dangerous precedent for the patenting of elements and atomically-engineered matter.

1974 Norio Taniguchi of Tokyo Science University first uses the word "nanotechnology."

1981 Gerd K. Binnig and Heinrich Rohrer at IBM's Zurich Research Laboratory invent a scanning tunneling microscope that enables researchers to see and manipulate atoms for the first time. The researchers won a patent on the microscope in 1982 and a Nobel Prize in Physics in 1986.

1981 Eric Drexler publishes the first technical paper on molecular nanotechnology in the *Proceedings of the National Academy of Sciences.*

1985 Robert F. Curl Jr., Harold W. Kroto and Richard E. Smalley discover Buckminsterfullerenes (buckyballs) measuring approximately 1 nanometer wide.

1989 IBM physicists manipulate atoms precisely by spelling the letters I-B-M with thirty-five xenon atoms.

1991 Sumio Iijima, a physicist at NEC Research Labs in Japan discovers multi-wall carbon nanotubes.

1993 Warren Robinett of the University of North Carolina and R. Stanley Williams of the University of California create a virtual reality system connected to a scanning tunneling microsope that enables researchers to "see" and touch atoms.

1993 Rice University establishes the first laboratory dedicated to nanotechnology in the USA.

1996 Curl, Kroto and Smalley win Nobel Prize in chemistry for discovering buckyballs.

1997 The first nanotechnology venture capital company established in the USA.

1998 Researchers at the Delft University of Technology (Netherlands) create a transistor from a carbon nanotube.

2000 Lucent and Bell Labs, working with Oxford University, create the first DNA motors, demonstrating the convergence of biotech and nanotech.

2001 Researchers at both IBM and Delft University use carbon nanotubes to develop nanometer-sized logic circuits–the components that perform processing in computers.

2001 Mitsui & Co. of Japan announce plans for mass-manufacture of carbon nanotubes.

2002 In June IBM's nanotechnologists demonstrated data-storage density of 1 trillion bits per square inch, equal to a 100-gigabyte hard-drive–enough to store 25 million printed textbook pages on a surface the size of a postage stamp.

2002 In August IBM announces the development of a new electron microscope with resolving power less than the radius of a single hydrogen atom.

Sources: Gary Stix, "A Few 10-9 Milestones," in Scientific American, September 2001, p. 36 and CMP Cientifica, Nanotech: The Tiny Revolution, and Douglas Mulhall, Our Molecular Future, Prometheus Books, 2002; and ETC Group.

Notes

1 CMP Cientifica, "Nanotechnology Opportunity Report," March 2002. CMP Cientifica's report focuses only on new technology that involves material smaller than 100nm; it estimates annual sales derived from nanotechnology to be US$30 million, though Scott Mize, the originator of the report, stated that the estimate excluded revenues from tools and that it may be about US$70 million short (Foresight Basic Tutorial, October 10, 2002). Due to the report's prohibitive cost (US$1995), ETC's references come from a summary of the report: Eric Pfeiffer, "Nanotech Reality Check: New Report Tries to Cut Hype, Keep Numbers Real," *Small Times*, March 11, 2002; available on the Internet: www.smalltimes.com. The NanoBusiness Alliance, a newly-minted US trade group, estimates nanotechnology's annual global revenues to be US$45.5 billion. The enormous discrepancy is due to the Alliance's inclusion of some products that are not truly nano-scale—a strict but widely accepted definition of nanotechnology limits the size of what is being manipulated to less than 100 nanometers. The Alliance figure includes MEMS—microelectrical mechanical systems, which are on the scale of micrometers. CMP Cientifica's figure excludes some products that are truly nano-scale but not new technologies (e.g., carbon black, nano-scale carbon particles—chemically the same as soot—have been used in the manufacture of tires for almost a century).

2 M. Roco and W.S. Bainbridge, eds., "Societal Implications of Nanoscience and Nanotechnology," National Science Foundation, March 2001, pp. 3-4.

3 Gary Krist, *Extravagance, A Novel.* Broadway Books, 2002, p. 21.

4 See John Gribbin, Science: A History 1543-2001, Penguin/Allen, 2002, as reviewed in "A History of Science—Time's Arrow," *The Economist*, Sept. 28, 2002.

5 Carlo M. Cipolla, *Before the Industrial Revolution-European Society and Economy*, 1000–1700, (Third Edition), W. W. Norton & Company, 1994, pp. 105.

6 *Ibid*., pp.105-107.

7 Kevin Phillips, *Wealth and Democracy*, Broadway Books, 2002, p. 258.

8 *Ibid*., p. 258.

9 *Ibid*., p. 259.

10 Krist, *Extravagance*, p. 11.

11 Phillips, *Wealth and Democracy*, pp. 175-176.

12 *Ibid*., pp. 175-177.

13 *Ibid*., p. 260.

14 Anonymous, "Bigger is Better," *The Economist*, February 26, 1998.

15 Phillips, *Wealth and Democracy*, p. 262.

16 Anonymous, "Bigger is Better," *The Economist*, February 26, 1998.

17 The term was first used in 1974 by Norio Taniguchi of Tokyo Science University according to Douglas Mulhall, *Our Molecular Future*, 2002, Prometheus Books, p. 32.

18 David Rotman, "The Nanotube Computer," *Technology Review*, March 2002, p. 38.

19 According to Joseph Cross, President and CEO of Nanophase Technologies. Available on the Internet: www.nanophase.com/ceo_interview01_02.pdf

20 John Emsley, *Nature's Building Blocks: An A-Z Guide to the Elements*, Oxford University Press, 2001, p. 2.

21 *Ibid*., p. 6.

22 Claudia Hume, "The Outer Limits of Miniaturization," *Chemical Specialties*, September 2000.

23 This illustration borrowed from "Nanotechnology: Shaping the World Atom by Atom," p. 3. Available on the Internet: itri.loyola.edu/nano/IWGN.Public.Brochure/

24 Richard Feynman, "There's Plenty of Room at the Bottom," 1959; available on the Internet: www.zyvex.com/nanotech/feynman.html

25 Richard P. Terra, "Manipulating Atoms and Molecules With the Scanning Tunneling Microscope and Atomic Force Microscope,"1998; available on the Internet: www.nanozine.com/NANOTOOL.HTM; see also, Mitch Jacoby, "New Tools for Tiny Jobs," *Chemical and Engineering News*, Oct. 16, 2000, p. 33.

26 K. Eric Drexler, *Unbounding the Future: The Nanotechnology Revolution*, Quill William Morrow, 1991, pp. 92-94.

27 An image of the historic nano-logo can be seen on the Internet: www.almaden.ibm.com/vis/stm/images/ibm.tif

28 IBM's Binnig played a major role in the development of the AFM, too, winning US Patent 4,724,318 in 1986 (reissued as patent USRE33387 on Oct. 16, 1990).

29 Personal communication with Veeco Metrology, Santa Barbara, CA, September, 2002.

30 John Markoff, "New Electron Microscope is Developed at I.B.M. Lab," *New York Times*, August 8, 2002.

SECTION II

2

The discoverer
of an art is not
the best judge
of the good or
harm which will
accrue to those
who practice it.

Plato, *Phaedrus*

ATOMTECHNOLOGIES' FOUR (RISKY) STEPS DOWN

For the Environment, the Economy and Life Itself

In this section

etc Group examines present-day and future applications of Atomtechnology in four stages. These stages are not universally accepted or defined—but represent our best effort to categorize and explain the range of present and future Atomtechnologies. The four "steps down" are not necessarily sequential and they are not mutually exclusive, nor does the advent of each new step herald the retirement of the previous step. Steps 2, 3 and 4 all contribute to the convergence of nano-scale technologies with biotechnology, informatics and neurosciences. The steps outlined below are discussed in more detail in the following pages.

STEPPING DOWN: STEP 1 · "BULK NANO" refers to present day applied Atomtechnology. It involves the bulk production of nano-scale particles (pure elements and simple compounds) for today's "atomic commodity" market. Bulk sprays, powders and coatings are used in the manufacture of products such as crack-resistant paints, automobile air bags, sunscreens, stain-repellant fabrics, self-cleaning windows and solar panels. Nanoparticles can contribute to stronger, lighter, cleaner and "smarter" surfaces and systems. Step 1 also includes the manufacture of molecules of pure carbon known as nanotubes and **buckyballs** (see box p. 23).

STEPPING DOWN: STEP 2 · NANOFABRICATION The goal here is to manipulate and assemble nano-scale particles into **supra-molecular** constructions and even larger structures that have practical uses. The products of nanofabrication are still in the tiniest and invisible realm of nanodevices—less than 100 nanometers in size.

STEPPING DOWN: STEP 3 · MOLECULAR MANUFACTURE This application of Atomtechnology, considered the ultimate goal by some, and a pipe dream by others, takes Step 2 out of the invisible realm. The goal is to use some system of mass production, possibly self-replicating nano-scale robots, to manufacture any material good on any scale.

STEPPING DOWN: STEP 4 · ATOM AND EVE (BIONIC NANO) This refers to the use of nanomaterials to affect biochemical and cellular processes. Bionic nano could be as simple as using nano-engineered materials for artificial joints, or as complex as developing bio-nano hybrids—using nanomachines in the human body to perform cellular functions or putting living matter to work as nanomachine parts or combining non-biological and biological material to create new materials with useful properties, including being able to self-assemble or self-repair.

Are some of these sub-sets of the new technology safe and others not? Are some more fiction than science? How will these Atomtechnologies disrupt the environment? How will they affect the economy?

STEPPING DOWN 1: Bulk nano—Nanoparticle Production

"We have had the Stone Age, the Bronze Age, and the plastic age... The future is the designed material age."

Shuguang Zhang
associate director of mit's center for biomedical engineering.[1]

Step 1 accounts for most of the products associated with Atomtechnology today. It involves the production of nano-scale particles (pure elements, simple compounds and **composites** for use in bulk sprays, powders, and coatings). Step 1 also includes the tools needed to produce and manipulate nanomaterials. Veeco, a New York-based company is particularly notable in the field of tools and equipment. After acquiring three afm manufacturers and key intellectual property, Veeco dominates the world market in atomic force microscopes,[2] reportedly controlling 89 percent of the global market.[3] The market for atomic force microscopes is projected to grow from us$181 million to $800 million by 2007.[4]

An estimated 140 companies worldwide are producing nanoparticles today.[5] The world market for nanoparticles is projected to rise 13% per annum, exceeding us$900 million in 2005.[6] Today, nanoparticles are being used in the manufacture of scratch-proof eyeglasses, crack-resistant paints, anti-graffiti coatings for walls, transparent sunscreens, stain-repellant fabrics, self-cleaning windows and ceramic coatings for stronger solar cells. Nanoparticles can contribute to stronger, lighter, cleaner and "smarter" surfaces and systems.

At the nano-scale, the properties of particles may change in novel and unpredictable ways. Nanoparticles of zinc oxide used in sunscreens, for example, have the same chemical composition and formula (ZnO) as the larger zinc oxide particles—the white glop that has been slathered on lifeguards' noses for decades—but nano ZnO is transparent. Antimony-tin oxide provides another example. When nanoparticles of antimony-tin oxide are incorporated into a coating, they become scratch-resistant and offer transparent protection from uv radiation.

According to Richard Siegel of the Rennselaer Polytechnic Institute, one of the leaders and breeders of the Clinton White House's National Nanotechnology Initiative, even the manufacture of nanoparticles will bring about an industrial transformation that will eclipse Europe's Industrial Revolution of the late eighteenth and early nineteenth centuries. Siegel's exuberant vision is all the more impressive since he sees this new economy being driven solely by the production of nanomaterials and dismisses the possibility of self-replicating machinery as science fiction (see Step 3).

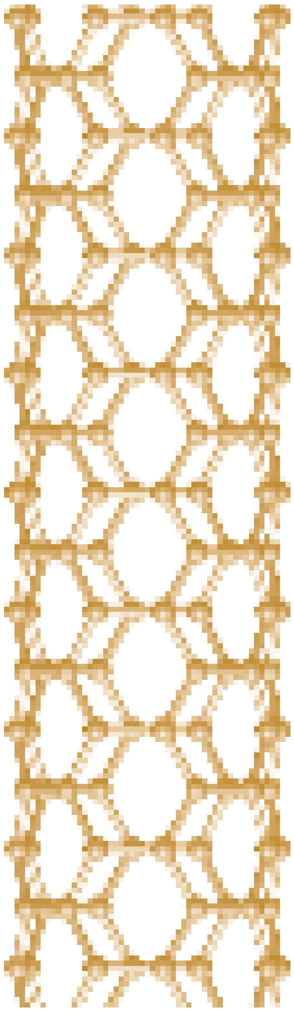
MIRACLE MOLECULES: Step 1 also includes the manufacture of molecules of pure carbon known as nanotubes and buckyballs. Nanotubes and buckyballs belong to the same chemical family called fullerenes. But when people refer to fullerenes, they usually mean buckyballs. The discovery of nanotubes and buckyballs is important because these molecules have unique properties with enormous commercial applications. Nanotubes are 100 times stronger than steel and six times lighter; they conduct electricity better than copper and can also act as semi-conductors. Some predict nano-scale carbon transistors will replace silicon transistors within the next ten years. Before that can happen, industry must be able to scale-up nanotube manufacturing techniques so that they can produce the tubes cheaply and uniformly. In 1999, the cost of buckyballs was around us$600/gram. Just three years later, the cost had dropped to about $30/gram. Industry analysts predict that, with rapid advances in production processes, the price of buckyballs will fall to $10/gram by the end of 2002.[7] Japanese innovators claim that they will take down the price of nanotubes by 90 percent in one year.[8]

WHAT ARE NANOTUBES AND BUCKYBALLS? Both buckyballs (a.k.a. fullerenes) and nanotubes are molecules consisting solely of carbon atoms. Buckyballs are one of three crystalline forms of carbon: graphite and diamond are the other two forms. Buckyballs (short for buckminsterfullerenes) are perfect spheres, made of sixty carbon atoms arranged like the pentagons and hexagons that make up the surface of a soccer ball. They are named after R. Buckminster Fuller, the inventor who promoted the geodesic dome as the ideal architectural structure. When people refer to fullerenes, they usually mean buckyballs. Nanotubes are a member of the fullerene chemical family, but of course they are not spherical. As their name suggests, nanotubes are long and thin and shaped liked tubes. They can be hollow like straws (known as single-walled) or rolled up inside each other like posters stored in a mailing tube (known as multi-walled).

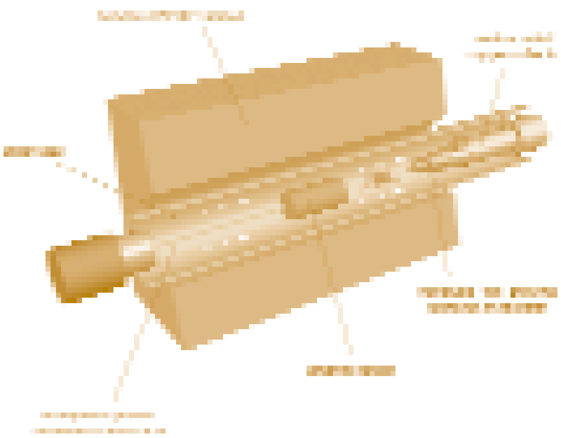
WHY ARE THEY IMPORTANT? Nanotubes are hailed as Atomtech's "miracle material" because they exhibit characteristics that make them ideal for an impressively broad range of applications, from space-craft- and automobile-manufacturing to electronics–including transistors and fuel cells–to biosensors and drug delivery. Nanotubes are 100 times stronger than steel and six times lighter; they can be as small as 1 nm in diameter and as long as 100,000 nm. Depending on how they are configured, nanotubes are good conductors of electricity and can also act as semi-conductors for molecular electronics.

DO CARBON NANOTUBES AND BUCKYBALLS OCCUR NATURALLY? It depends on what you mean by "natural." Carbon is a plentiful element on earth, in the foods we eat and in our bodies; it is also plentiful in outer space and is given off by dying stars. The brightest star in the night sky, known as CW Leonis, is particularly interesting to carbon researchers because it is surrounded by a haze of carbon molecules, some with large numbers of carbon atoms. In 1985, collaborating scientists in England and the USA were able to replicate this interstellar environment in their laboratories. They discovered buckyballs among the carbon molecules that had formed.[9] Unlike buckyballs, nanotubes are not known to exist naturally in either the earth's environment or in outer space. Nanotubes were discovered in 1991 by Sumio Iijima of Japan while he was experimenting with a method of producing buckyballs. Scientists can now make nanotubes and buckyballs at will and in bulk.

HOW ARE NANOTUBES AND BUCKYBALLS MANUFACTURED? Both these types of carbon molecules are self-assembled, meaning that when conditions are just right, they form into their distinctive configurations all on their own. There are several different methods for making nanotubes and buckyballs. Almost all the methods begin with a common form of carbon (usually graphite) and a small amount of metal (used as a catalyst). When the graphite and metal are heated to extreme temperatures (around 1200 degrees Celsius, in one method), the carbon breaks up into individual atoms. When the carbon atoms condense, they configure themselves into tubes or spheres.



A side view of a metallic nanotube. Copyright V. H. Crespi. Distributed under the OpenContent license *opencontent.org/opl.html*



Nanotubes can be produced by aiming a laser at a block of graphite, vaporizing the graphite. Contact with a cooled copper collector causes the carbon atoms to form into tubes. Illustration by Aaron Cox/American Scientist. Used with permission.

"In a field with more than 12,000 citations a year, we were stunned to discover no prior research in developing nanomaterials risk assessment models and no toxicology studies devoted to synthetic nanomaterials."

Vicki Colvin
director of the center for biological and environmental nanotechnology, rice university[78]

The French tennis-racquet manufacturer Babolat already incorporates nanotubes into its "Nanotube VS" racquets, but they could also be used to strengthen and lighten all kinds of materials, including synthetic bone implants and artificial joints. Because nanotubes are good conductors of electricity, they are raising hopes for faster, more accurate diagnostics in the biomedical field and more efficient drug delivery methods.[10] A Stanford University chemist, for example, is working to develop a glucose sensor using a single carbon nanotube, which could be implanted into patients with diabetes.[11] Referring to nano-scale carbon's potential applications in medicine, Nobel Laureate and Rice University (Texas, usa) professor Richard Smalley waxes witty: "A thousand years from now I would be amazed to wake up from a cryogenic sleep and find there was any answer to this other than [nano]tubes."[12] Due to their semiconducting properties, nanotubes may be the building blocks for smaller, faster computers and nanotube transistors have been shown to outperform silicon transistors.[13]

GETTING DOWN TO BUSINESS: Nanotubes and buckyballs are being manufactured in laboratories worldwide. Technically, it isn't possible to patent nanotubes or buckyballs because they are discoveries, not inventions. But innovators are racing to stake claims in the nano gold rush by winning patents on novel methods to produce nanotubes and buckyballs. Over 200 patents involving carbon nanotubes were filed or issued in 2001; almost half of those patents cover their synthesis and processing.[14] The 2004 market for nanotubes is pegged at us$430 million.[15] Industry analysts predict that the nanotube market will explode to billions of dollars once commercial methods allow for faster, cheaper production. An estimated fifty-five companies are making carbon nanotubes and at least twenty companies are gearing up for commercial-scale production (hundreds of tons annually) of buckyballs.[16] Rosseter Holdings Ltd. has been producing nanotubes in Cyprus since 1998.[17] Two Japanese companies have just been launched to make them in bulk quantities: Frontier Carbon Corporation (a joint venture of Mitsubishi Corp. and Mitsubishi Chemical Corp.) plans to produce 40 tons of nanotubes next year and Carbon Nanotech Research Institute aims for an annual production of 120 tons.[18] In 2002 California-based NanoDevices, Inc. began selling a make-it-yourself nano-carbon oven—the "EasyTube NanoFurnace"—for us$89,000.[19]

WHAT ARE THE RISKS? Until recently, nanoparticles were widely embraced as beneficial and totally benign. However, in March 2002 researchers made the astonishing revelation that nanoparticles are showing up in the livers of research animals, can seep into living cells, and perhaps piggyback on bacteria to enter the food chain. These unexpected findings have been under-reported and largely ignored in the mainstream media. Concerns over Step 1 Atomtechnology were first voiced by scientists from the Center for Biological and Environmental Nanotechnology (cben) at Rice University at a fact-finding meeting at the US Environmental Protection Agency in Washington, DC.[20] According to Rice's Mark Wiesner, tests measuring the accumulations of materials in the livers of laboratory animals demonstrate that nanoparticles, even inorganic ones, will accumulate within organisms: "We know nanomaterials have been taken up by cells. That sets off alarms...If bacteria can take them up, then we have an entry point for nanomaterials into the food chain."[21] Equally alarming, Wiesner pointed out the need to examine whether nanoparticles absorbed into bacteria enhance the ability of other materials, including toxic ones, to piggyback their way into the bacteria and cause damage. Wiesner asked, "Suppose we can't control nanoparticles the same way we control powders?"[22] Will the quality that makes nanoparticles so attractive for the development of efficient drug-delivery systems—namely, their ability to easily enter the bloodstream and even target individual cells due to their small size—also be the quality that makes them dangerous to humans?

Rice University researchers are particularly concerned about the commercial use of carbon nanotubes. Wiesner, who is a professor of Civil and Environmental Engineering, asks, "Where does this stuff go? What will be its interaction with the environment? Is it the next best thing to sliced bread or the next asbestos?"[23] Wiesner points out that companies are now looking into using carbon nanotubes in radial tires. Old used tires are ubiquitous from backyards to landfills to lake bottoms and groundwater. Will nanotubes be as well?

Dr. Wiesner's comparison of carbon nanotubes with asbestos is not merely rhetorical. Carbon nanotubes resemble asbestos fibers in shape: they are long and needle-like. According to Dr. Wiesner, carbon nanotubes cannot pose much of a threat at present because, in our environment, they tend to clump together rather than exist as single fibers (which have the potential to cause serious respiratory problems as asbestos fibers have). However, an intensive area of research is to figure out a way to solubilize nanotubes—in effect, to de-clump them—so that they can be more easily used as single, detached fibers.[24] Two patents on methods of solubilizing nanotubes in organic solutions have issued in the last year to the University of Kentucky (usa).[25] Very few studies have been done to learn what might happen if nanotube fibers were breathed in or if they were used in drug delivery, disease diagnoses or as biosensors.

News item: Nanoparticles accumulate in the livers of laboratory animals.

"There may be a slight problem...but it's just an itsy-bitsy teeny weeny one!"

Some industry advocates dismiss concerns about the asbestos-like health threats posed by carbon nanotubes, pointing to a 2001 study conducted at the University of Warsaw, Poland. Researchers injected nanotubes into the tracheas of guinea pigs. Four weeks later, the lungs of the guinea pigs showed no measurable inflammation or change in function. The authors of the Polish study reached this sweeping conclusion: "Thus, working with soot containing carbon nanotubes is unlikely to be associated with any health risk."[26] (Setting tobacco smoke to the same standards, smoking would probably be declared a perfectly safe activity!)

Immunologist Silvana Fiorito working in Montpellier, France has discovered in preliminary research that when a 1 micrometer-wide particle of pure carbon (in the form of graphite) is introduced into a cell, the cell responds by producing nitric oxide, which indicates that the immune system is working and the body is fighting back against an invading foreign substance.[27] When a nano-sized particle of the same substance—pure carbon—is added to cells (in the form of either nanotubes or bucky-balls), the cells fail to produce an immune response—they welcome the alien carbon like a long lost relative. The ability to slip past the immune system may be desirable for drug delivery, but what happens when uninvited nanoparticles come calling? In other words, once nanotechnologists have figured out how to distract the bouncer guarding the door, how can you be sure you're still keeping out the riff-raff?

Despite recent findings of potential risks related to Step 1 Atomtechnology, and despite the fact that governments worldwide are spending billions of dollars to spur commercial scale nanobusiness, there is no regulatory body (and no plans for one) dedicated to overseeing this potent and powerfully invasive new technology. The US Environmental Protection Agency, for example, currently allots no more than 10 percent of its nanotech research grants for the "environmental benefits and potential harmful effects of nanotechnology at a societal level." Given the potentially huge implications for the environment and human health, the societal implications of a completely new economy of manufacture need to be understood—now.

ETC Evaluation

Because present day Atomtech generally works with the elemental building blocks of life–rather than with life directly–it has largely evaded social, political and environmental scrutiny. Regulatory bodies have thus far established no policies or protocols for considering the safety of Step 1 Atomtechnology, which includes nanoparticles in products already on the market and new forms of nano-scale carbon. At this stage, we know practically nothing about the potential cumulative impact of human-made nano-scale particles on human health and the environment. Given the concerns raised over nanoparticle contamination in living organisms, governments should declare an immediate moratorium on commercial production of new nanomaterials and launch a transparent global process for evaluating the socio-economic, health and environmental implications of the technology.

ETC Evaluation

All the risks of Step 1 apply to Step 2. In addition, however, nanofabricated products may have biomedical applications that will bring nano-scale devices into intimate contact with the human body. The perils are unknown.

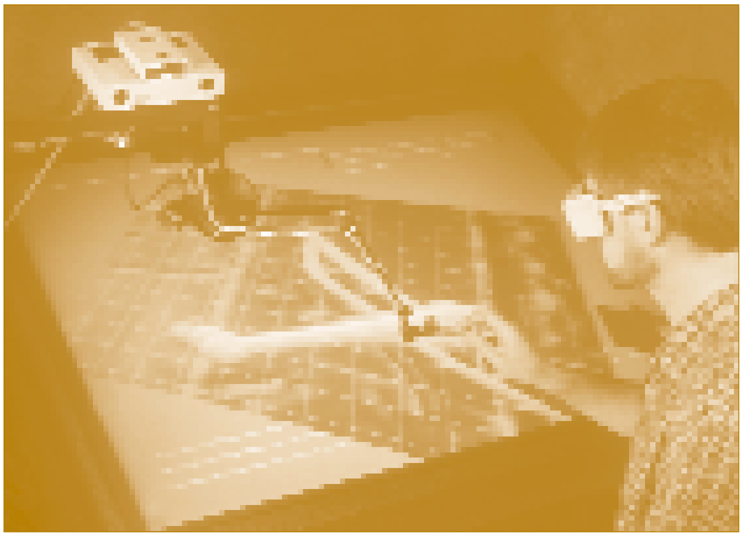
STEPPING DOWN 2: Nanofabrication: Building from Atomic Scratch

As we have seen in Step 1, nanotechnologists have already been able to manufacture nanoparticles and to harness the phenomenon of **self-assembly** to make nanotubes. In order to move from the manufacture of individual particles with useful properties (Step 1) to complex and useful structures made from multiple molecules (Step 2), self-assembly is the key. Self-assembly refers to the process of using catalysts and energy to carefully control chemical reactions to achieve desired results spontaneously. Scientists have observed chemical self-assembly for decades with results on the micro scale (and on the beaker scale for even longer); now they are working toward nano-scale results.

The goal of Step 2 is to manipulate and assemble nano-scale particles into supra-molecular constructions and even larger structures that have practical uses. This is known as nanofabrication. It involves designing molecular building blocks that automatically snap together in pre-designated ways. It is important to stress that nanofabrication is *not* about building chairs or houses or computers by means of molecular self-assembly. The final product of Step 2, nanofabrication, is still in the invisible nano-realm—*smaller than 100 nanometers*.

Figuring out how to build working structures from atomic and molecular scratch is still in the early stages. Products of nanofabrication are being developed for use as electronic circuitry, biosensors or new **polymers** that manipulate light in optical communication systems. The desire to build ever-smaller, faster and cheaper electronic devices is driving the quest to move down from micro to nano. In the words of Harvard University chemists George Whitesides and J. Christopher Love, "The microelectronics mold is now broken."[28]

The race is on to figure out how to build nanostructures faster and cheaper. Researchers are exploring every plausible method, including both "top-down" and "bottom-up" techniques. Several forms of lithography (the traditional method of fabricating circuits on microchips) are being modified to produce nanometer-scale structures—but shrinking this "top-down" process is cumbersome, slow and expensive. Alternatively, researchers are using "bottom-up" methods that start from atoms or molecules and build up to working nanostructures. Nanotubes could become the ideal materials for building nanodevices—once researchers learn how to control and manipulate their special properties.



Physicist Martin Guthold uses the nano Workbench, part of the nanoManipulator system, to investigate the mechanical and electrical properties of a stack of carbon nanotubes. Photo by Larry Ketchum. Used with permission.

Within a few years, the use of molecules as circuit elements is expected to become a commercial reality and enormously lucrative. Electronic firms such as Motorola and Samsung are already testing prototypes of nanotube televisions (flat screen, high definition TVs). If molecular transistors work, carbon nanotubes could replace silicon as the building blocks for ultra-fast computers that perform "orders of magnitude" beyond silicon.[29] (Using today's state-of-the-art microelectronics, 42 million transistors are crammed onto Intel's Pentium 4 chip. By contrast, nanotube computers of the future would feature chips hosting *billions* of molecular transistors.[30])

STEPPING DOWN 3: Molecular Manufacture—Invisible Goliaths

Some believe that scientists will one day be able to control atomic-positioning so completely and precisely that any object whose atomic composition is known (from buildings to buffets) could be assembled from its primary parts. The art of atom-by-atom construction on the macro scale is called **molecular manufacture** or **molecular nanotechnology**. The difficulty lies in directing the atoms to assemble themselves in the desired configuration—and doing it fast enough to get a turkey on the table in time to feed the great, great grandkids. A lively debate revolves around the extent to which molecular manufacturing will be possible.

Though Steps 1 and 2 are realities, Step 3 is still in the conceptual phase. While many mainstream scientists assert that Step 3 will never arrive, there are others who fervently believe that it will be possible to program matter with molecular precision on the macro-scale sometime "in our lifetimes and the lifetimes of our children."[32]

Beyond simply incorporating nanoparticles into conventional materials to improve their performance (Step 1), some scientists aim to custom-build macro-sized objects completely out of nano-scale components, building from the bottom up. Such objects can have entirely new properties never before identified in nature. If a ceramic brick or a metal part, for example, were to be made completely from nanoparticles, the surface area would increase dramatically because the smaller the object, the greater proportion of its atoms are at or near the surface.[33] Though the chemical composition would remain the same and only the parts' sizes would have changed, the increased surface area would mean that the nano-built brick or metal piece might be harder, less likely to crack, or more resilient under stress (pressure, temperature, light, etc.).

> *"But I am not afraid to consider the final question as to whether, ultimately—in the great future—we can arrange the atoms the way we want; the very atoms, all the way down!"*
>
> **Richard Feynman**
> "There's Plenty of Room at the Bottom," 1959[31]

VISIONS OF MASS CONSTRUCTION: But the real vision of Step 3—first elaborated by K. Eric Drexler in his *Engines of Creation: The Coming Era of Nanotechnology* (1990)—allows making entire cars or houses using atom-by-atom construction, a colossal step beyond incorporating nanostructured components into a conventionally manufactured car or house. In Drexler's vision, a computer's nanotube transistor would not be the single nanofabricated element embedded in an otherwise manufactured computer (Step 2); rather, the whole thing—screen, circuitry, keyboard, disc drive and cardboard box—would be fabricated as a unit, atom by atom. Drexler calls Atomtech's Step 3 molecular nanotechnology and sometimes refers to it as *molecular manufacture* or *machine-phase nanotechnology*. As difficult as it is to imagine, any object—"computers, rocket engines, chairs, and so forth," according to Drexler—could be created by programming the right molecules to assemble in the right configurations.

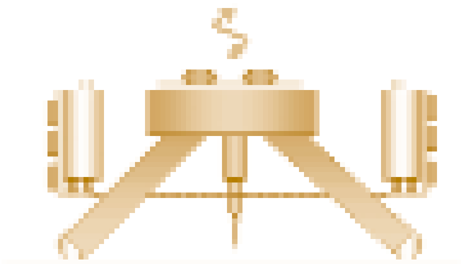
One Step 3 scenario would have an Atomtech engineer in front of a computer screen attached to a souped-up atomic force microscope programming nanobot modules to reconfigure themselves to build living room furniture from the atom up. Another Step 3 scenario might have a hungry teenager logging onto the Internet to buy and download the blueprint for a hamburger. He slips a plastic-looking sheet of elements into the family nanobox and out pops the hamburger, ready to eat. Could these scenarios become realities? How?

AUTO-ASSEMBLERS: Drexler predicts that the work of atom-by-atom construction will be performed by computer-directed nano-scale robots called **assemblers**—little Henry Fords laboring in factories the size of cells. The factories will contain nanomachines mounted on a molecular framework with conveyor belts that move parts from machine to machine. The cell-sized factories will have a set of programmable assembler arms on the outside that can reproduce and repair themselves. Drexler believes that nano modules will be available which are relatively uniform and interchangeable and can be retooled depending on what you want built. Since the entire world is constructed from hardly a hundred different building blocks (the Periodic Table)—and most, like our own bodies, lean heavily on only a handful—"ikea" style construction could come to a computer near you. (ikea is a popular Swedish "put-it-together-yourself" furniture store chain that has spread worldwide.) Although the final products could be "macro," the construction process would be "nano" and virtually invisible.

THUMBELINA WITH AN ATTITUDE: Giant steps are already being taken in the direction of nano-scale robots. Researchers at the Massachusetts Institute of Technology (mit) BioInstrumentation Laboratory have developed hundreds of three-legged robots, each the size of a thumb. The robots are equipped with onboard computers, biosensors and scanning tunneling microscopes and are capable of measuring and assembling structures on the molecular scale. Only 32 millimeters high, the microbots (dubbed "NanoWalkers" because they are able to make 4,000 nanometer-sized maneuvers per second) are designed to respond to infrared signals allowing each microbot to act independently or collectively on myriad tasks. The tiny machines are capable of executing 48 million instructions per second. mit predicts it will soon have over 100 microbots hard at work on separate but related tasks in an enclosed card table-sized chromium-coated chamber. The chromium surface provides an energy source for the robots, which will receive their marching orders from a master computer in the box's ceiling.[34]

In the near future, mit scientists anticipate that the micro-army will have the power to manipulate individual molecules and even re-arrange atoms. Capable of making 200,000 measurements per second, the machines may initially be used to analyzechemicals and to assist in the development of new pharmaceuticals. However, there is no obvious limit to their job description, including the assembly and repair of fellow microbots and the eventual construction of still-tinier nanobots.

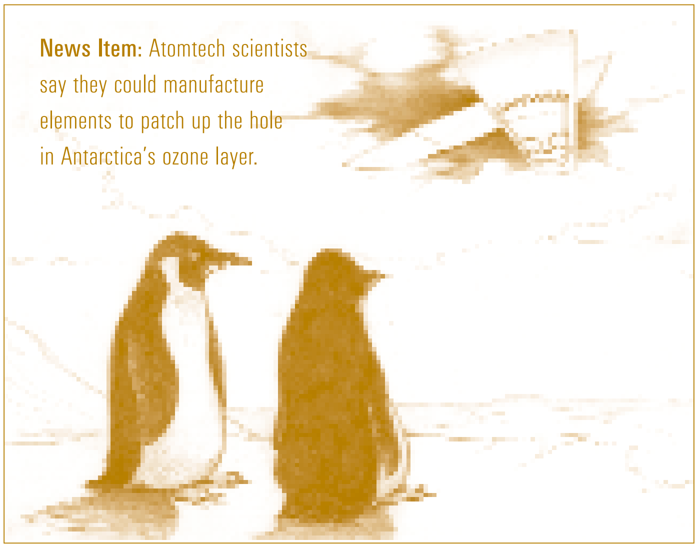
ATOMIC SEX: Amazing as they are, NanoWalkers can't perform the one function that will allow Step 3 to become a reality as Drexler envisions it: they can't procreate. **Self-replication** refers to the ability of Drexler's assemblers to make copies of themselves as well as being able to configure atoms and molecules en masse. The idea of self-replicating assemblers is the "sticking point" for most chemists and physicists because they believe it cannot be achieved. But how else could molecular manufacture become a reality? Atoms are so small that cobbling anything together one atom at a time—or even one molecule at a time, at the rate of one assemblage per second, for example—would take longer than the history of the world to build something the size of the head of a pin.[35] A single gram of carbon contains 50,000,000,000,000,000,000,000 atoms—just assembling enough of them to make the graphite to fill one pencil would become the life's work of Father Time.[36] But if assemblers could be created that were capable of producing copies of themselves (called **replicators**) and if assemblers and replicators could cooperate to work in unison, in a kind of combination nano-scale assembly-line and barn-raising, they would be able to create products on the macro-scale.[37] Armies of self-replicating nanobots could build everything from a Big Mac to a Mac Apple to the Big Apple. A battalion of a trillion nanobots would still be too small to be seen with the naked eye.[38]



MIT's "NanoWalker" Robot
32mm tall

SPLITTING HAIRS? Most scientists dismiss nanofabrication on the macroscale as the stuff of Hollywood movies or science-fiction novels. A "debate" over the likelihood that self-replicating nanomachines will exist one day appeared in *Scientific American*'s September 2001 issue. Drexler reiterated his vision of constructing large-scale objects with molecular precision using assemblers capable of self-replication. Richard Smalley (see Step 1) categorically discounted the possibility: "Self-replicating, mechanical nanobots are simply not possible in our world. To put every atom in its place—the vision articulated by some nanotechnologists—would require magic fingers. Such a nanobot will never become more than a futurist's daydream."[39] George Whitesides, who has built working nanostructures using self-assembly (see Step 2), also dismisses Drexler's molecular nanotechnology. He wrote, "We don't know how to make self-replicating machines of any size or type today…no sense of how to design a self-sustaining, self-replicating system of machines."[40] (Drexler and colleagues at his Institute for Molecular Manufacturing have composed detailed rebuttals of Whitesides's and Smalley's objections, which are available on the Internet.[41])

Though Drexler thinks nanomachines can be created using the familiar machinery of our mechanical world as the model, he continually turns to the biomolecular world for inspiration. He explains, "In growing, healing, and renewing tissue, the body is a construction site. Cells take building materials from the bloodstream. Molecular machinery programmed by the cell's genes use these materials to build biological structures: to lay down bone and collagen, to build whole new cells, to renew skin, and to heal wounds...everything in the human body is constructed by molecular machines. These molecular machines [i.e., assemblers] build molecules, including more molecular machines [i.e., replicators]."[42] Whitesides, too, recognizes the success of nature's nanomachinery but maintains that "it would be a staggering accomplishment to mimic the simplest living cell."[43]



News Item: Atomtech scientists say they could manufacture elements to patch up the hole in Antarctica's ozone layer.

Are mechanical self-replication and large-scale molecular manufacture just the pipe dreams of overconfident engineers? We can be sure that large-scale manipulations of matter are in our near future even if they don't come about in the precise ways that Drexler theorizes. There may be other options for getting large-scale, mass production without relying on either assembly lines peopled with underpaid workers or self-replicating nanobots. The most promising option may be to harness and redirect nano-machines that already exist in nature (see Step 4) or to start thinking *inside* the box.

NO ASSEMBLY REQUIRED? A team of student-researchers at Georgia Institute of Technology has been experimenting with "space-based manufacturing," where particles are placed inside zero-gravity boxes and then subjected to particular frequencies of sound.[44] The sound alone has the ability to levitate the particles and move them around. By varying the shape of the box and the frequency of the sound, researchers have been able to push the particles to form desired structures, all on their own. The research group has refined the technique of "acoustic shaping" to the point where they can form curved surfaces and cylinders. To date, the cost is prohibitive and the scale is "laboratory" rather than "industrial," but, according to researchers, sound-based manufacturing offers enormous potential: large-scale manufacture from composite particles and no assemblers required!

What are the risks?

GRAY GOO What if nanobots start building chairs and don't stop? The self-replicating and assembly processes could go haywire until the world is annihilated by nanobots or their products. Gray Goo refers to the obliteration of life that could result from the accidental and uncontrollable spread of self-replicating assemblers. Drexler provides a vivid example of how quickly the damage could pile up beginning with one rogue replicator. "If the first replicator could assemble a copy of itself in one thousand seconds, the two replicators could then build two more in the next thousand seconds, the four build another four, and the eight build another eight. At the end of ten hours, there are not thirty-six new replicators, but over 68 billion. In less than a day, they would weigh a ton; in less than two days, they would outweigh the Earth; in another four hours, they would exceed the mass of the Sun and all the planets combined."[45] To avoid a Gray Goo apocalypse, Drexler and his Foresight Institute, a non-profit organization whose purpose is to prepare society for the era of molecular nanotechnology (MNT), have established guidelines for developing "safe" MNT devices. Foresight recommends that nano-devices be constructed in such a way that they are dependent on "a single artificial fuel source or artificial 'vitamins' that doesn't exist in any natural environment." Foresight also suggests that scientists program "terminator" dates into their atomic creations[46] and update their computer virus-protection software regularly?

AND SPIES, TOO "Intelligent," invisible, self-replicating nanobots capable of receiving remote directions and altering programmes spell the death of dissent. In a world not dedicated to diversity and democracy, it will be possible for those who have power to stifle all opposition.

STRANGE NEW WORLD If scientists figure out how to use the Periodic Table of Elements in the same way that a painter uses a palette of pigments, industry will be able to manipulate materials in ways that were impossible to control at the macro or micro scale. **Quantum modeling**, which allows researchers to use computers to predict how nano-scale materials will perform according to the rules of quantum mechanics, will also aid in designing materials that have never been made before.[47] With a powerful enough computer, scientists will be able to custom-design a material atom by atom, building in desirable properties with a stroke of the keyboard. Even if nano-construction is presented as "natural" compared to conventional manufacture, the construction processes may leave the world filled with full-sized products as strange to nature as anything devised by genetic engineers. All the risks of Steps 1 and 2 continue to apply to Step 3, with enormous additional risks in the event that self-replicating nanomachines become possible.

ATOMIC BAND-AIDS Beyond the production of nano materials as building blocks, it may also be possible to use the extraction of specific elements or compounds to alter the environment (Drexler imagines "disassemblers" that would work in the opposite direction of assemblers, breaking down substances atom-by-atom, either for analysis or for extracting raw materials). Some suggest that Atomtech is our only hope for preventing natural catastrophes resulting from earthquakes, climate change or asteroid collisions. To survive a giant plume of volcanic dust in the atmosphere, for example, we could unleash "sky bots" that would consume dust particles as feedstock and self-replicate into the trillions.[48] Others speculate that they might be able to "seed" the oceans to better absorb pollutants–or "seed" the stratosphere to patch up holes in the ozone layer. The implications of such experimentation are unknown but profoundly troubling. Rather than confront the underlying problems of over-consumption and waste, industry could see Atomtechnology as a means to "medicate" a solution for the earth. Are we in need of a band-aid solution (that could, in fact, spell new concerns) or will we address the realities of the world we have made?

CARBON COPIES Atom-by-atom construction makes it theoretically possible for Atomtechies to build life. People, after all, are 99% hydrogen, nitrogen, oxygen and carbon. (The average adult lugs around 16 kilos of carbon; see box page 12) Most of the remaining 1% comes from 15 other elements ranging from phosphorus to cobalt to radioactive potassium-40. A single human cell contains about 450,000 atoms of cobalt and 135 million zinc atoms, for example.[49] "Life" may be little more than getting the recipe right. A technology that can create life can also–save for accidents and design–end death. We are far from prepared to address the issues raised by Atomtechnologies.

NUCLEAR-POWERED NANOBOTS The issue of a power source for tiny machines is becoming terribly important. While some scientists research the possibility of using laser light as a fuel source, others are proposing that machines functioning at the micro-level should be powered by nuclear batteries.[50] Researchers at the University of Wisconsin-Madison (USA) have received a three-year, $970,000 US Department of Defense (Defense Advanced Research Projects Agency–DARPA) grant to develop the technology.[51] Is it the "peaceful use of the atom" once more with feeling?

STEPPING DOWN 4: Atom and Eve—Bionic Nanotechnology

This is where Atomtechies merge biological and non-biological materials into bionic products and processes. This merging could "blend" people with robots. Since the 1960s, science and popular culture have called such creations "cyborgs" (short for "cybernetic organisms"). Theoretical physicist Stephen Hawking makes the sad observation that merging with machines may be the only way for the human race to become intelligent enough to avoid being completely taken over by them.[55]

An amputee with a prosthetic leg and heart patients with battery-operated pacemakers implanted in their chests could be labeled first-generation cyborgs, but Atomtech will enable human-and-machine mergers the likes of which have never before been possible. Step 4 will result from nano-scale manipulations that allow non-living nanomaterials and living matter to become compatible and in some cases interchangeable. At the nano-scale, the distinction between biological and non-biological material blurs.[56]

The living and non-living nano-realms will merge on a two-way street. Living material will be extracted and manipulated to perform mechanical functions and to enable the development of hybrid materials that combine biological and non-biological material (Bio-nano I). Biological material is plentiful, cheap and exhibits useful properties—such as self-assembly—that non-biological material doesn't. Using different technologies, non-living material will be used within living organisms to perform biological functions (Bio-nano II).

"The question now is not whether it is possible to produce hybrid living/nonliving devices but what is the best strategy for accelerating its development."

Carlo D. Montemagno[54]

Atom and Eve

PROTEINS WORKING OVERTIME (BIO-NANO I):

- Researchers are putting nanomaterials derived from living cells to work in the service of (and as) machines. A team of researchers at Rice University has been experimenting with F-actin, a protein resembling a long, thin fiber, which provides a cell's structural support and controls its shape and movement.[57] Proteins like F-actin, descriptively called filamentous proteins, allow the transportation of electricity along their length. The researchers hope these proteins can one day be used as biosensors—acting like electrically conductive nanowires. Protein nanowires could replace silicon nanowires, which have been used as biosensors but are more expensive to make and would seem to have a greater environmental impact than protein nanowires.
- A researcher at Rennselaer Polytechnic Institute is stuffing proteins inside carbon nanotubes, which will then be incorporated into materials to make them "self-healing."[58] For example, protein-filled nanotubes may be incorporated into the plastic that makes up an airplane wing. If the wing becomes damaged and the nanotubes break apart, the released proteins could act as an adhesive and repair the damage.
- A complex working nanomachine with a biological engine has already been built by Carlo Montemagno at Cornell University (Montemagno is now at the University of California at Los Angeles, Department of Mechanical and Aerospace Engineering). Montemagno and his team of researchers extracted a rotary motor protein from a bacterial cell and connected it to a "nanopropeller"—a metallic cylinder 750 nm long and 150 nm wide. The biomolecular motor was powered by the bacteria's adenosine triphosphate (known as atp—the source of chemical energy in cells) and was able to rotate the nanopropeller at an average speed of eight revolutions per second.[59] Montemagno's team announced at the end of October 2002 that by adding a chemical group to the protein motor, they have been able to switch the nanomachine on and off at will.[60]

- A chemist at New York University is seeing if he can take advantage of dna's ability to self-assemble to create circuits. "Bioelectronics" may provide the path to ultra-small and ultrafast computers.[61]
- The motto of NanoFrames, a self-classified "biotechnology" company based in Boston, is "Harnessing nature to transform matter." That motto also makes a concise description of how Bio-nano I works. NanoFrames uses protein "subunits" to serve as basic building blocks (derived from the tail fibers of a virus called Bacteriophage T4). These subunits are joined to each other or to other materials by means of self-assembly to produce larger structures. As the company's web site (www.nanoframes.com) explains, the design of the subunits determines the final structure and requires no additional manipulation of individual molecules. NanoFrames calls their method of manufacture "biomimetic carpentry," but that label, while wonderfully figurative, comes up short. Using proteins as building blocks and taking advantage of their ability to self-assemble is more than imitating the biological realm (*mimesis* is Greek and means *imitation*)—it is more than turning to biology for inspiration—it is transforming biology into an industrial labor force.

MARRIAGES BASED ON COMPATIBILITY (BIO-NANO II): Merging the living and non-living realms in the other direction—that is, incorporating non-living matter into living organisms to perform biological functions—is more familiar to us (e.g., pacemakers, artificial joints), but presents particular challenges at the nano-scale. One major development in the convergence of new technologies is the integration of nanotechnology and biotechnology, now called **nanobiotechnology**. Researchers at Rice University have called this challenging nano-realm the "wet/dry" interface—where "wet" refers to the biological system and "dry" refers to the nanomaterials.[62] Roughly one-fifth (21%) of nanotech businesses in the usa are focused on the wet/dry interface, as they develop nano-scale pharmaceutical products, drug delivery systems and other healthcare-related products.[63] Because nanomaterials are, in most cases, foreign to biology, they must be manipulated to make them biocompatible, to make them behave properly in their new environment.

OLYMPIC NANO (BIO-NANO II): Researcher Robert Freitas is developing an artificial red blood cell that is able to deliver 236 times more oxygen to tissues than natural red blood cells.[64] The artificial cell, called a "respirocyte," measures one micron in diameter and has a nanocomputer on board, which can be reprogrammed remotely via external acoustic signals. Freitas predicts his device will be used to treat anemia and lung disorders, but also will enhance human performance in the physically demanding arenas of sport

HISTORICAL CUE II

Life "Unzipped"[52] Feats of Clay

Elements, my dear Watson: According to some legends, God breathed into molded clay and Adam took his first breath. Moses came down from the mountain bearing two tablets of clay upon which were embedded the code for what some might call the Book of Life. Now it seems the stories might be closer to reality than some expected. Clay may inscribe the formula to make life…if not how to live it.

In 1953, Watson and Crick identified DNA's double-helix and Stanley Miller launched science on an exploration of the origins of life. Working at the University of Chicago, Miller tried to create life from inanimate matter by brewing a primordial soup to mimic earth's oceans and environment. He replicated lightening storms by shooting electric volts into the soup. Within a few days, Miller's soup had produced more than a dozen amino acids including six of the twenty key building blocks for proteins.

Miller's work benefited from a hypothesis developed by Alexander Cairns-Smith in which the Scottish chemist concluded that "life" arose from nano-scale irregularities in the crystal lattice of clay minerals. This created the first genetic information and the opportunity for mutation as sheets of similarly irregular crystals were layered on the original clay.

This theory of the origins of life still has currency. Recently, researchers at Israel's Weizmann Institute used clay minerals to develop amino acids and a substance that, in the end, bore the chemical structure of a protein.

A modest variation on the clay theme was devised by a German patent attorney, Günter and warfare. Freitas states that the effectiveness of the artificial cells will critically depend on their "mechanical reliability in the face of unusual environmental challenges" and on their biocompatibility. Among the risks, considered rare but real, Freitas lists overheating, explosion and "loss of physical integrity."

REMOTE CONTROL DNA (BIO-NANO II): Researchers at mit, led by physicist Joseph Jacobson and biomedical engineer Shuguang Zhang, have developed a way to control the behavior of individual molecules in a crowd of molecules.[65] They affixed gold nanoparticles (1.4 nm in diameter) to certain strands of dna. When the gold-plated dna is exposed to a magnetic field, the strands break apart; when the magnetic field is removed, the strands re-form immediately: the researchers have effectively developed a switch that will allow them to turn genes on and off. The goal is to speed up drug development, allowing pharmaceutical researchers to simulate the effects of a certain drug that also turns genes on or off. The mit lab has recently licensed the technology to a biotech startup, engeneOS, which intends to "evolve detection and measurement *in vitro* into monitoring and manipulation at the molecular scale in cells and *in vivo*."[66] In other words, they intend to move these biodevices out of the test tube and into living bodies.

Wächtershäuser (following an atomic tradition set by another German patent examiner, Albert Einstein). Nanoparticles of pyrite—formed by iron-sulfur compounds—bequeathed the energy needed to create macromolecules en route to living organisms.

Thanks to the work of Cairnes-Smith, Miller and Wächtershäuser, many scientists now believe that it will be possible to build "life" via the atom-by-atom construction of inorganic matter. Further, "life" might spring not only from carbon but also from a variety of elements or compounds including clay iron-sulfur ("fool's gold"). At the outset of his thesis on clay minerals, Cairns-Smith quotes Sherlock Holmes, musing about the origins of life... "Odd, Watson [and Crick?]—very odd."[53]

Super-Colliding Technologies

When nano-scale technologies converge, the changes to life as most of us live it will be dramatic and personal. In December 2001, two US government agencies co-sponsored a workshop titled "Converging Technologies for Improving Human Performance." The collaboration between the chief science agency and the "voice of business in government"—the National Science Foundation (NSF) and the Department of Commerce (DOC)–resulted, unsurprisingly, in a marketing plan for new technologies. The workshop participants—from government, academia, and the private sector—focused on ways that convergent technologies—specifically, nanotechnology, biotechnology, informatics and cognitive sciences (the convergence is referred to as NBIC)—could "enhance" the physical and cognitive capabilities of humans, both individually and collectively. In other words, the question of the day, in the words of one participant, was how can convergent technologies "make us all healthier, wealthier and wiser?"[67] The answer to that question weighs in at over 400 pages. With only a smattering of critical analysis and few calls for caution, the benefits of enhancement are repeated again and again. NBIC will make us smarter (by allowing us to access and store more information in our brains or through the development of artificial intelligence), younger (by stopping or reversing the aging process), healthier and, of course, thinner (by controlling metabolism). The NSF/DOC report recommends a "national R&D priority on converging technologies focused on enhancing human performance," including "The Human Cognome Project," a multidisciplinary effort to understand the structure, functions, and potential enhancement of the human mind.

A few workshop participants urged that the social sciences be included in a nano-bio-info-cogno-socio convergence, but the social sciences were largely understood to operate in the service of NBIC.[68] Gerold Yonas and Jessica Glicken Turnley's contribution, for example, proposes "Socio-Tech," which they envision as a *predictive* science of societal behavior.[69] Through the "accumulation, manipulation, and integration of data from the life, social, and behavioral sciences," Socio-Tech would be able to "identify drivers for a wide range of socially disruptive events and allow us to put mitigating or preventive strategies in place before the fact."[70] The authors see Socio-Tech as a powerful weapon in the war on terrorism. In another example, James Canton, CEO of a California-based high-tech consulting firm, recognizes that "different cultures will define human performance based on their social and political values." On the heels of this acknowledgement, however, he asserts, "it is for our nation to define these values and chart the future of human performance."[71]

Gregor Wolbring, a biochemist at the University of Calgary and founder of the International Center for Bioethics, Culture and Disability, offers one of the rare, critical perspectives contained in the 400+ page report.[72] His contribution states explicitly that human performance should not be seen in a solely medical or technological context. He calls for a broader perspective in order to understand that the concepts of enhancement, progress, disability and disease are societal constructions and therefore technological "progress" should be examined critically for its relevancy and appropriateness.[73]

The report's recommendation for a national R&D initiative on converging technologies for human performance enhancement promises benefits on a truly biblical scale—"sightless who will see...lame who will walk...infertile couples who will be able to conceive children."[74] Perhaps its most disturbing aspect is the promise of a future in which all difference is erased—differences of language, intellect, imagination, age, physical characteristics, any characteristic that may be seen as "disruptive." The implications for the erosion of human rights, including the rights of those who are "un-improved"—either by choice or lack of choice—and for the erosion of democratic dissent are awesome. Will physical "enhancement" through new technologies become a social imperative? Will "self-improvement" become enforceable by law?[75]

The US government's draft report is an unsettling view of the scope, power and persuasion of converging technologies. The report is especially chilling as unabashed Atomtech boosterism by government, scientists and private sector representatives who see consumer acceptance as the key to increased funding for their work. The contributors make repeated references to products that will change and upgrade the lives of consumers–ranging from the frivolous to the fantastic. Converging technologies, we are told, may offer "active and dignified life far into a person's second century," but also wearable computers disguised as "scintillating jewelry," cosmetics that change with the user's moods and "smart clothing" that adjusts to the wearers's social environment.[76] It seems that Atomtech enthusiasts are trying desperately not to repeat the biotech industry's biggest blunder of the past decade. By failing to produce any genetically modified products with consumer benefits, the agricultural biotech industry today suffers from a lack of consumer acceptance and trust. In its zeal to shape public opinion and win consumer acceptance, the NSF/DOC report is evidence of a dangerous exercise in public relations and marketing to advance converging technologies.

What are the risks?

NEW MATTERS When Step 3 (molecular manufacturing)–in whatever form it ultimately takes–combines with Step 4 (bionic nano), Atomtech will create both living and non-living hybrids previously unknown on earth. The environmental implications of such new creations–some that could have the half-life of the universe–are incomprehensible.

VIVA EX-VIVO Human-made nanomachines that are powered by materials taken from living cells are a reality today. It won't be long before more and more of the cells' working parts are drafted into the service of human-made nanomachines. As the merging of living-nano and non-living nano becomes more common, the idea of self-replicating nanomachines seems less and less like a "futurist's day-dream." In his dismissal of the possibility of molecular manufacture (see Step 3), George Whitesides stated that "it would be a staggering accomplishment to mimic the simplest living cell." But we may not have to "reinvent the wheel" before human-made, self-replicating creations are possible; we can just borrow it. Whitesides believes the most dangerous threat to the environment is not Gray Goo, but "self-catalyzing reactions," that is, chemical reactions that speed up and take place on their own, without the input of a chemist in a lab."[77] It is here–where natural nanomachines merge with mechanical nanomachines–that Whitesides's warning resonates strongest.

SIX DEGREES OF HUMANITY Can societies that have not yet come to grips with the nature of being human soldier on to construct partially-human, semi-human or super-human cyborgs?

NATURAL BORN KILLERS As the merging of living cells and human-made nanomachines develops, so will the sophistication of biological and chemical weaponry. These bio-mechanical hybrids will be more invasive, harder to detect and virtually impossible to combat.

ETC Evaluation

For those who do not accept the risk of Drexler's Gray Goo, there is still the looming issue of a "Gray New World" posed by super-smart machines, unlimited surveillance capacity and a governing elite that becomes "Big Cyborg Brother" to us all. The power of nano+info+cogno is exponential and poses a major threat to democracy and dissent.

But there is an additional concern. Perhaps it is not the Gray Goo we need to fear but the "Green Goo." Rather than try to manufacture self-replicating machinery that mimics the self-replication of living materials, it is more likely that we will take control of living materials and use them to mimic machinery. This is already happening at the level of microorganisms, but it might also include higher life forms. For example, the military is finding that the modification of insects for military or industrial objectives could be a much simpler task than creating mechanical flying machines of similar size. In the end, will the "Green Goo Revolution"—the takeover of life for industrial functions—pose the greater risk?

Who will colour your world?

Gray Goo Theory: SORCERER'S APPRENTICE	Blue/Gray Goo Theory: BRAVE NEW WORLD	Green Goo Theory: TOYS'R US
Invisible self-replicating mechanical robots multiply uncontrollably until their hunger for raw materials (natural elements) and energy consumes the world.	Super machines evolve to manage complex human and environmental systems and (eventually) either take over the world or fall into the hands of a corporate elite that rules omnipotently.	Scientists combine biological organisms and mechanical machines for industrial uses. The organisms continue to do what nature intended–they procreate–but they've been made more powerful by their boost from human technology: the emboldened bacteriophage becomes the omniphage.

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69 Gerold Yonas works at the Sandia National Laboratories, operated by defense industry contractor, Lockheed Martin, under contract to the US Department of Energy. Sandia develops emerging technologies to promote national security. Jessica Glicken Turnley is an anthropologist and head of Galisteo Consulting Group, Inc.
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SECTION III

3

You know,

things are going

to be really

different!...

No, no, I mean

really different!

Mark Miller to
K. Eric Drexler
mid–1980s[1]

WILL ATOMTECHNOLOGIES WORK?

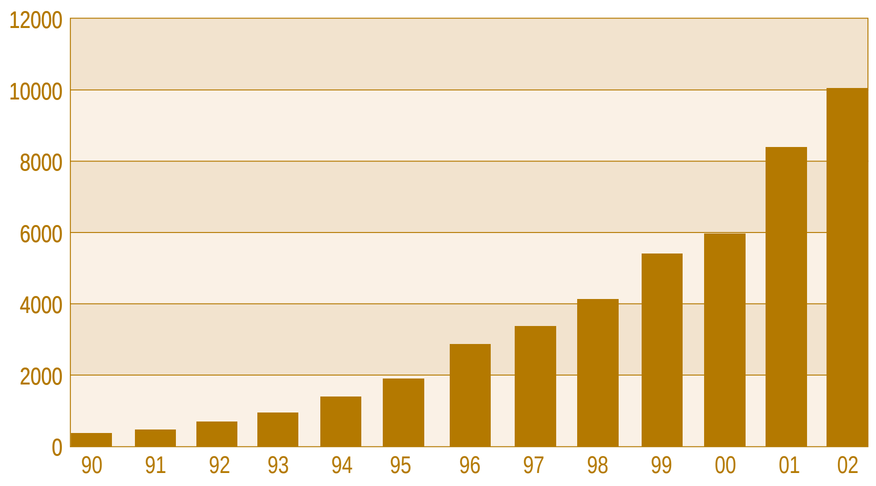
Four tests for a new technology

It wasn't just the mention of "nanotechnology" in recent Hollywood blockbusters ("Spiderman" and "Minority Report") that made us sit up and take notice. etc Group determined that it was time to take nano-scale technologies seriously when we evaluated the hype against four measurements: (1) the number of citations recorded in the scientific literature; (2) the number of nano-related patents being filed; (3) the sums of money being invested in basic research and (4) the range and reputation of the public and private institutions undertaking the research. It takes a critical mass for a science to become a viable technology in the marketplace. Here are the details…

LOOK WHO'S TALKING 1: **Nano-nerds—the scientific citations**

A database of citations provided by isi Citation Index tracks all references to key words in peer-reviewed English language scientific publications. In 1987, the scientific literature included about 200 "nano" references. By the end of 2001, there were roughly 7,700 "nano" citations for the year. In just the first six months of 2002 there were over 6,000 nano citations.[2]

Nanotech Science Notations 1990–2002



As importantly, references to "nanotechnology" have moved beyond the conventional scientific press to popular science and business media. In September 2001, for example, *Scientific American* devoted its entire issue to nanotech. In December 2001, *Chemical and Engineering News* also featured nanotechnology as its cover story. *USA Today*, the *People* magazine of daily newspapers, now has a nanotechnology reporter. Virtually every issue of *Technology Review* features a nanoscience breakthrough. With increasing regularity, the business press is talking "nano" and centerfold spreads making references to nanotech are commonplace.

There is clearly a critical mass of scientific thinking and research underway. In recent years, several Nobel Prizes have gone to scientists whose work relates directly to Atomtechnologies. The following table lists the "Nano-Nobel" Laureates since 1990 in Physics and Chemistry alone. Several other nano-related connections could also be made for the Nobels in Medicine but these are more complicated to isolate.

Nano Nobels of Physics and Chemistry (1990 – 2001)

	Name(s)/Year	Why They Won	Institute
PHYSICS	**2001** Eric A. Cornell Wolfgang Ketterle Carl E. Wieman	"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates;" the new "control" of matter which this technology involves may bring revolutionary applications in such fields as precision measurement and nanotechnology.	Cornell and Wieman work at JILA, an institute run jointly by the University of Colorado and NIST (National Institute of Standards and Technology, USA). Ketterle is at Massachusetts Institute of Technology, USA.
PHYSICS	**1998** Robert B. Laughlin Horst L. Störmer Daniel C. Tsui	"for their discovery of a new form of quantum fluid with fractionally charged excitations;" this has led to yet another breakthrough in our understanding of quantum physics.	Laughlin is at Stanford; Störmer is at Columbia; Tsui is at Princeton (all US-based universities).
PHYSICS	**1997** Steven Chu Claude Cohen-Tannoudji William D. Phillips	"for development of methods to cool and trap atoms with laser light"	Chu is at Stanford (USA); Cohen-Tannoudij is at the Collège de France and École Normale Supérieure (France); Phillips is at the NIST (USA).
PHYSICS	**1996** David M. Lee Douglas D. Osheroff Robert C. Richardson	"for their discovery of superfluidity in helium-3"	Lee and Richardson are professors in the Physics Department at Cornell (USA). Osheroff worked for 15 years at Bell Labs and now teaches at Stanford (USA).
CHEMISTRY	**2000** Alan J. Heeger Alan G. MacDiarmid Hideki Shirakawa	"for the discovery and development of conductive polymers"	Heeger is at University of California Santa Barbara (USA); MacDiarmid is at University of Pennsylvania (USA); Shirakawa is at University of Tsukuba (Japan).
CHEMISTRY	**1999** Ahmed H. Zewail	"for his studies of the transition states of chemical reactions using femtosecond spectroscopy"	Zewail is at the California Institute of Technology (Pasadena, USA).
CHEMISTRY	**1998** Walter Kohn John A. Pople	Kohn "for his development of the density-functional theory" and Pople "for development of computational methods in quantum chemistry"	Kohn is at University of California Santa Barbara (USA); Pople is at Northwestern University (USA).
CHEMISTRY	**1996** Robert F. Curl Jr. Harold W. Kroto Richard E. Smalley	"for their discovery of fullerenes"	Curl and Smalley are at Rice University (USA); Kroto is at University of Sussex (UK). Smalley founded Carbon Nanotechnologies, Inc., which produces single-wall carbon nanotubes.
CHEMISTRY	**1991** Richard R. Ernst	"for his contributions to the development of the methodology of high resolution nuclear magnetic resonance (NMR) spectroscopy"	Ernst directed the Physical Chemistry Lab of the ETH Zurich and retired in 1998.

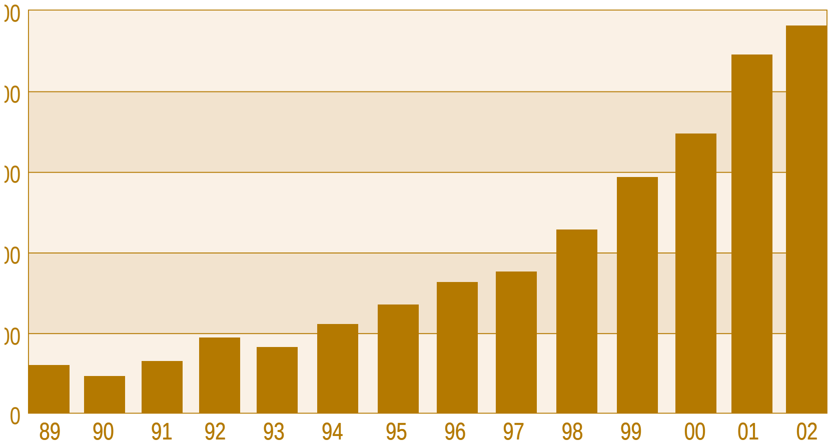
Source: The Nobel Foundation, *www.nobel.se*

LOOK WHO'S PATENTING 2: Nano-nabobs and nano-nichers—multinational corporations and nano start-up companies

Back in the late '80s, there were about 60 patents that made reference to "nano" in their applications. At the close of 2001, nearly 445 claims were granted during the year, and the number of nano-related patents is expected to exceed that level by the end of 2002.[5] Whereas the biotech industry had to overcome a number of legislative prohibitions (that living material was non-patentable, for example) to secure intellectual property over organisms and their component parts, Atomtechies face far fewer constraints, giving matter moguls a substantial edge over genetic engineers.

It is not only the number of patents but *who* is making the claims. The companies include the "Who's Who" of Fortune 500 firms. The world's most prestigious university campuses are also involved. The nano start-up companies are not alone in the field; the big industrial giants are already developing Atomtech expertise internally—not holding back the way they did when biotechnology first appeared on the horizon. Interestingly, but not surprisingly, among the most aggressively filing for nanotech-related patents are the US Navy and the US Army.

US Nano-Related Patents 1989–2002



LOOK WHO'S PAYING 3: Nanobodies and nanobuddies—Taxpayers and Public Science Researchers

Pioneers in new technologies universally consider themselves ignored and undervalued. The biotech boutiques of the '70s complained bitterly about the disinterest of the venture capital market. So, too, do the 'start-ups' of Atomtech. Nevertheless, the cash flow into basic research and new products is impressive. In 2001, global spending on the industry's fundamentals (both corporate and government) was approximately $4 billion.[6] Boom spending on basic research during a recession is no modest testament to the technology's potential.

Also in keeping with the biotech model, Atomtech is traveling on the backs of taxpayers ("nano-bodies") and public science ("nano-buddies"). And, as ever, the profits will accrue to the elite academic entrepreneurs and the industrial giants that ultimately absorb the most promising start-ups.

Spending on basic nanoscience research by governments is defying the economic laws of gravity. Even as the global economy spins into recession, Japan and the usa are running neck-and-neck to out-spend each other in publicly-supported research. The European Union is behind but determined to catch up.

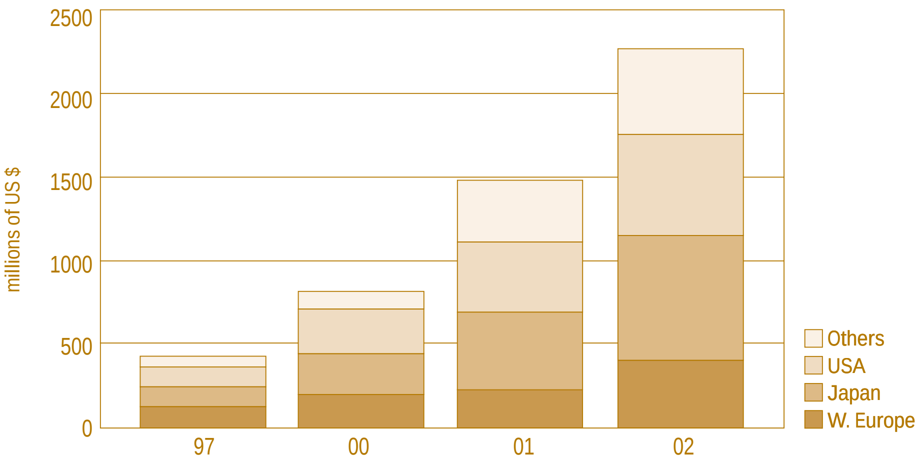
Nanoscientists in the usa are described as "giddy" about the federal commitment to nanotechnologies.[7] US government spending totaled $463 million in 2001; will top $600 million in 2002; and will hit $710 million in 2003.[8] In 2002, Japanese government spending on nanotech pulled ahead of the usa, and the EU comes in a close third. Global government expenditures in 2001 exceeded us$1 billion and more than doubled to almost us$2.5 billion in 2002.[9] (See chart below for more information on individual countries' nano-investments).

"Nanotechnology is the builder's final frontier."

Richard Smalley, 1996
Nobel Prize Laureate, Chemistry[3]

Aside from governments, a key indicator of commercial potential lies in the interest shown by venture capitalists. US venture capital investment has grown from a modest $100 million per annum in 1999 to $780 million in 2001 and will be a "bullish" $1.2 billion in 2003.[10] This is a "post-September 11th" industry estimate.

In addition to government and venture capital funds, the third great source of research money comes from the "in-house" activities of multinational enterprises. Companies as varied as Xerox, Toyota, DuPont, Siemens AG, General Electric, basf and Hewlett-Packard appear to be investing heavily in nanotech, but are reluctant to disclose spending levels. By some reckonings, the Fortune 500 is thought to be matching government and venture capital spending combined.



Global Government Investment

Others includes Australia, Canada, China, E. Europe, FSU, Israel, Korea, Singapore, Taiwan.

Source: M. C. Roco, www.nano.gov/intpersp_roco.htm

Is $4 billion a year spent globally on R&D sufficient to spawn a new industrial revolution? The US military, by comparison, spends about $1.2 billion a year developing unmanned aerial vehicles (uavs). But uavs are well beyond the initial research phase and even saw extensive action in Afghanistan. Atomtechnology stands today where biotechnology stood at the end of the '70s and where semi-conductors were at the end of the '60s. Even accounting for inflation over the decades, $4 billion a year for basic research is impressive.

LOOK WHAT'S (ALREADY) HAPPENING 4: Nanobucks—from research to revenues

"Nanotechnology is the way of ingeniously controlling the building of small and large structures, with intricate properties; it is the way of the future, a way of precise, controlled building, with incidentally, environmental benignness built in by design."

Roald Hoffman, 1981
Nobel Prize Laureate, Chemistry[4]

The fourth indicator that Atomtech is "real" is that it is obviously making progress and already making products. In stark contrast to biotechnology's early days (and even today), Atomtechnology already has products in the marketplace and almost half of the start-up nano-nichers are selling their wares. According to cmp Cientifica, there are around five hundred "nanotechnology companies" evenly distributed throughout North America, Asia and Europe. A little over ten percent of those companies are in the business of producing nanotubes and fibers and about one third is selling the tools (e.g., atomic force microscopes) that will make the development of the technology possible.[11] Industry sources estimate that small technologies (including **microelectrical mechanical systems** [**MEMS**]) in the usa are already selling about $45.5 billion in goods and services and that, by 2005, revenues there will reach $225.5 billion.[12] By 2010 or so, the US National Science Foundation predicts annual sales of $340 billion for nanostructured materials and processes; $600 billion annually in electronics and informatics revenues; and sales of about $180 billion in pharmaceutical applications by 2015[13], with half of all pharmaceutical production dependent on nanotechnology. Annual global nanotech-related sales are expected to exceed $1 trillion by 2015. At that point, Atomtechnologies will be the dominant factor in the sectors of electronics (from computers to telecommunications), pharmaceuticals, energy and materials manufacturing.

Back in 1995, *Wired* magazine asked leading US scientists to speculate on Atomtech's progress in the years ahead.[14] Although the interpretations could vary, it would seem that the technology is thus far exceeding expectations. By 2000, more than two dozen US patents had been issued related to molecular assemblers, for example, and many researchers now believe that cell repair through Atomtech is close at hand. In one category, however, nanoscience developments are lagging behind: the majority of experts consulted believed that by 2000 there would be laws regulating nanotechnology in the US—they were wrong.

Start-up companies have found low costs and few barriers to the commercial introduction of nano-powders and materials. Similarly, the potential for nano-scale tools and parts in electronics is so vast that no industrial sector can ignore the field. Toyota already uses nanocomposite materials to strengthen plastics used in car parts. Nanopowders are finding uses in the making of UV-protected lenses, glass and coatings.

1995 Forecasts by Leading Atomtechnicians

Milestone	Hall	Smalley	Birge	Drexler	Brenner
Nano Regulations	1995	2000	1998	2015	2036
Commercialization	2005	2000	2002	2015	2000
Molecular assembler	2010	2000	2005	2015	2025
Cell repair	2050	2010	2030	2018	2035
Nanocomputer	2010	2100	2040	2017	2040

Source: *Wired*, August 1995

In 1987 the etc Group (then rafi) and the Dag Hammarskjöld Foundation hosted the world's first-ever civil society seminar on the social and economic impacts of biotechnology. The international meeting was held in Bogève, France and brought together activists from every continent. For almost all participants, it was their first serious look at biotechnology. For most, it was a shocking encounter and it took many a long time to realize that the talk about transgenic species wasn't just hype. In 2001, the Dag Hammarskjöld Foundation and the etc group joined forces again to host the world's first civil society seminar on Atomtechnologies. Held at the Foundation's Uppsala, Sweden offices, the seminar again brought together leading political and environmental activists from around the world. "Bogève II," as the organizers dubbed it informally, shocked most participants even more than Bogève I had fourteen years before. However, because many of those present had long histories in the biotech debate, they caught on quickly. The table below compares the development of biotech and Atomtech from Bogève I to Bogève II.

ETC Evaluation

By 2005, Atomtech will attract more interest (and controversy) than biotech. By 2010, Atomtechnologies will be the determining factor to profitability in virtually every sector of industrial economies. By 2015, the controllers of Atomtech will be the ruling force in the world economy.

Atomtech and Biotech –"It can't happen here ... again?"

BIOTECHNOLOGIES: Bogève I (1987)	ATOMTECHNOLOGIES: Bogève II (2001)
SCIENCE FICTION: It won't work outside the lab. Such engineering defies natural law.	
In the 1980s, conventional scientists in both agriculture and medicine often warned that genetic engineering would run afoul of the infinite complexity of nature; that what works in the lab would fail in real life. Maybe they were right...but today 55 million hectares are sown to GM crops, and biodrugs (GM pharmaceuticals) are proliferating.	Some scientists believe that manipulating the Periodic Table will run afoul of theories of energy and still unknown natural laws. But atoms are the next logical 'declension' from genes. Atomtech may not be safe, it may not work well, but it will be commercialised. It is not necessary to get it right to get it to market. As the first generations of GM products make clear, failure in science can still mean success in business.
PONDEROUS PROGRESS: It's generations away. We're just beginning.	
In the 1980s, most scientists thought biotech products were a long way off. They completely misjudged progress in computing and other enabling technologies that have both slashed costs and massively accelerated R&D.	Engineering machines or food atom-by-atom seems distant now but molecular assembly is on its way and continuing advances in informatics and other enabling technologies will bring new Atomtech products to market much faster than predicted.
HYPE: It's Wall Street propaganda. Desperate companies are trying to convince would-be investors that new products are just around the corner and will solve all the world's problems.	
In the 1980s, biotech 'boutiques' were struggling to survive and promising 'pie in the sky.' Many died out and the rest are still being bought out by the Gene Giants. After a slow start, new products (good or bad) are coming on stream fast. The world, however, appears no closer to Nirvana.	Nano-nicher start-ups are springing up now as bio-boutiques did before. There is the same 'silver bullet' hype. However, unlike biotech, the biggest corporations are getting in on the ground floor.
NICHE MARKET: It may work well in special cases but it will not have a wide impact on how we produce things.	
One Gene Giant argued in the 1980s that herbicide tolerance would only be viable to combat Johnson Grass in Texas. Today, three-quarters of the global transgenic area is in herbicide-tolerant varieties. 'Niche' market human genomics companies are mapping crop genomes. One of the most profound characteristics of biotech is its broad application in agriculture, pharmaceuticals, personal care products and industrial manufacture.	Some argue that Atomtech is a novelty; that it will only be used for highly specific purposes because of its cost and complexity. In fact, Atomtech's reach is greater—by far—than biotech. As the range of companies involved makes clear, Atomtech will dominate every aspect of the global economy.
NANOBUCKS: They are tiny and fragile. They don't have the clout needed for the science or the market.	
In the 1980s, biotech 'boutiques' were small, scarce and starving. The big agrochemical and pharmaceutical giants appeared uninterested and many predicted that the little upstarts would go bankrupt and the technology would fizzle.	The nano-nicher start-ups of today are also small, weak and struggling. The difference is that the Fortune 500 corporations—the 'Nano-nabobs'—are in hot pursuit of the new technology.
PATENTS & REGS: The governments don't provide the requisite patents or regulatory flexibility.	
They got it. By the late 1980s, the US Patent Office announced it would allow patents on plants and animals as well as microorganisms. The USDA, NIH and FDA regulations were being manipulated to accommodate industry needs.	They'll get it. Atomtech has fewer patent barriers. Biotech has already set legal precedents for sweeping claims. Regulatory constraints on 'atomic power' will be manipulated into ineffectiveness.

Notes

1 As quoted in Ed Regis, *Nano, the emerging science of Nanotechnology: remaking the world – molecule by molecule*, 1995, p. 133.

2 The citation search is based on the Institute for Scientific Information (ISI) citation index, using nano* as search term in titles. The figure for 2002 is extrapolated from the number of citations counted as of September 2002.

3 Cited in "Nanotechnology: Shaping the World Atom by Atom," p. 1. Available on the Internet: www.nano.gov

4 *Ibid*., p. 4.

5 The number of nano-related patents is based on a search conducted on Delphion using nano* as the search term. The figure for 2002 is extrapolated from the number of patents issued by mid-year.

6 Eric Pfeiffer, "Nanotech Reality Check: New Report Tries to Cut Hype, Keep Numbers Real," *Small Times*, March 11, 2002; Available on the Internet: www.smalltimes.com/print_doc.cfm?doc_id=3237

7 Doug Brown, "Nano for the Nation: Mihail Roco," *Small Times*, vol. 2, no. 4, July/Aug. 2002, p. 16.

8 Mike Roco, "Research and Development FY 2003: National Nanotechnology Investment: the FY 2003 Budget Request by the President" Available on the Internet: www.nano.gov/2003budget.html

9 Ann Thayer, "Nanotech meets market realities," *Chemical & Engineering News*, July 22, 2002, p. 18.

10 NanoBusiness Alliance, "2001 Business of Nanotechnology Survey," p. 4. Available on the Internet: www.nanobusiness.org

11 According to CMP Cientifica's "Nanotechnology Opportunity Report," as reported by Eric Pfeiffer, "Nanotech Reality Check: New Report Tries to Cut Hype, Keep Numbers Real," *Small Times*, March 11, 2002; Available on the Internet: www.smalltimes.com/print_doc.cfm?doc_id=3237

12 NanoBusiness Alliance, "2001 Business of Nanotechnology Survey," p. 4.

13 Mike Roco and W.S. Bainbridge, eds., "Societal Implications of Nanoscience and Nanotechnology," National Science Foundation, March 2001, pp. 3-4.

14 David Pescovitz, "Reality Check – The Future of Nanotechnology," *Wired*, August, 1995.

SECTION IV

4

[Nanotechnology] holds the answer, to the extent there are answers, to most of our pressing material needs in energy, health, communication, transportation, food, water, et cetera.

Richard Smalley
Rice University professor
and Nobel Laureate[1]

WHO AND WHERE WILL IT IMPACT?

The poor and the economy, of course

Trying to assess the impact of the BIG *Down* is not easy because the array of new names and technological approaches is so vast. Based on a study by the NanoBusiness Alliance (nba—a newly-minted US trade group), the present-day market for small technologies is around us$45.5 billion. That market will jump to us$700 billion around 2008 and exceed us$1 trillion probably well before 2015.[2]

Yet, in a 2001 year-end review of the economic future of new technologies in *The Economist*, the editors reported on a survey of informed business readers. According to their readership, the next big breakthrough in technologies is still most likely to come in the information sector (22%). Another 20% were betting on biotechnology. Nanotech, materials sciences and transportation technologies each garnered about 5%, but the third highest percentage went to those who felt that the next industrial revolution would come about through a convergence of new technologies.[3]

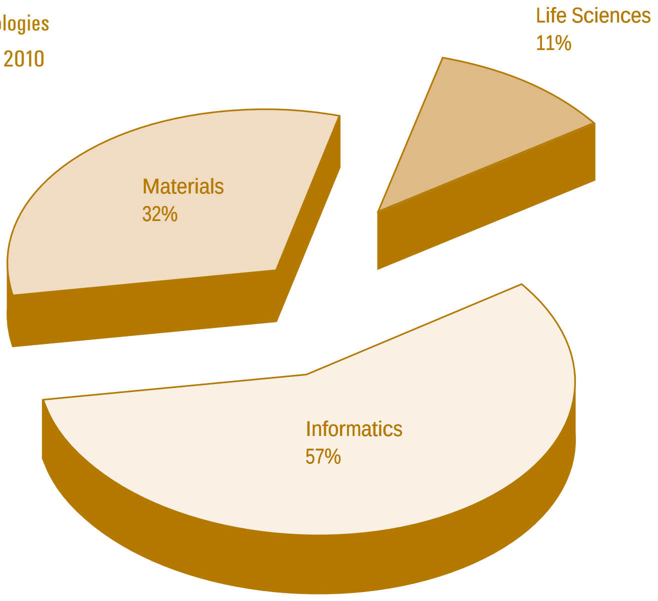
Nevertheless, an idea of the new technologies' likely impacts can best be suggested by considering each major economic sector. It goes without saying that the workers in each sector (and we're not referring to Nobel Prize-winning scientists), including those whose skills will no longer be needed or viable, will feel the impact first.[5]

"There are three, although I have a feeling that, under some future unified theory, they will turn out to be just one. The first is, of course, information technology…The second is biotechnology…And the third is nanotechnology."[4]

then-Chairman and CEO of Monsanto **Robert Shapiro**, when asked what he believed were the most promising future technologies

The Trillion Dollar Technologies

The Atomtech Market by 2010



Nanopolies

Twenty years ago, no one would have believed us if we warned (and we did!) that biotech companies would someday make it illegal for farmers to save seed; that they could sue farmers for the patented seed that blew onto their property; that not only plant varieties but individual genes and SNPs (single nucleotide polymorphisms) could be patented; that entire species and even human cell lines could be monopolized; that the traditional knowledge of a people could become the private property of a pharmaceutical giant.

Will it be possible someday to patent an element the same way corporations patent genes today? Will they only need to isolate and purify an element to own it? Nobel Laureate Glenn Seaborg was allowed to patent *americium* and *curium*—two of eleven elements he discovered half a century ago. Seaborg also "created" element 110, which is yet to be formally named. In 1999, nuclear physicists at the Lawrence Berkeley National Laboratory (USA) crashed krypton particles into lead and announced the discovery of two new elements—nos. 118 and 116. (It was later found that element number 118 was based on falsified data.)[6] But scientists believe that other elements will be found in nature eventually. Will such new elements be patentable?

How about patenting the processes needed to use an element? Will it be possible to modify an element and then patent the process and the product? Will there be process patents that bar traditional manufacture because conventional processes compromise the new monopoly? Will some of the new patentable inventions be cyborgs? In 2001, for example, researchers at the Brookhaven National Laboratory in the USA cranked up their Relativistic Heavy Ion Collider and smashed out an ancient sub-atomic particle known as "quark-gluon plasma." The US collider, together with its counterparts in other countries, is designed as a process to create new matter. Are these to be patentable inventions?

Or, as was done with nuclear energy, will the controllers of Atomtech insist that their tools are so powerful and so fundamental that they must operate with a state-enforced monopoly for reasons of national security?

"It is true that one cannot patent an element found in its natural form; however, if you create a purified form of it that has industrial uses—say, neon—you can certainly secure a patent."

Lila Feisee
Director for Government Relations and Intellectual Property, Biotechnology Industry Organization, April 11, 2001

MANUFACTURING AND MATERIALS

Nano-scale bulk commodities are already making money. Nanoparticles are being used to make paints and other coatings more durable or stronger, to make sunscreens more protective and to make catalysts more efficient. Studies show that a single gram of catalyst particles with a 10-nanometer diameter is about 100 times more reactive than the same amount of catalyst particles that are a micron in diameter. The change is attributable solely to the increased surface area of the nanomatter.[9] Largely through catalysis, nano-scale processes are transforming the global plastics industry, which is valued at us$60 billion per annum in the United States alone. Giant enterprises like Dow Chemical and Exxon Mobil license their variations on "metallocenes"—a nano-scale approach to creating catalysts for the manufature of plastics. The end products are lighter, tougher and amazingly more versatile. Exxon Mobil holds over 200 metallocene patents.[10] Dow has also worked at the atom-scale to contrive "interpolymers" (the development of the process has resulted in over 50 patents in the usa and Europe—previously unheard-of combinations of matter with unique commercial properties).[11]

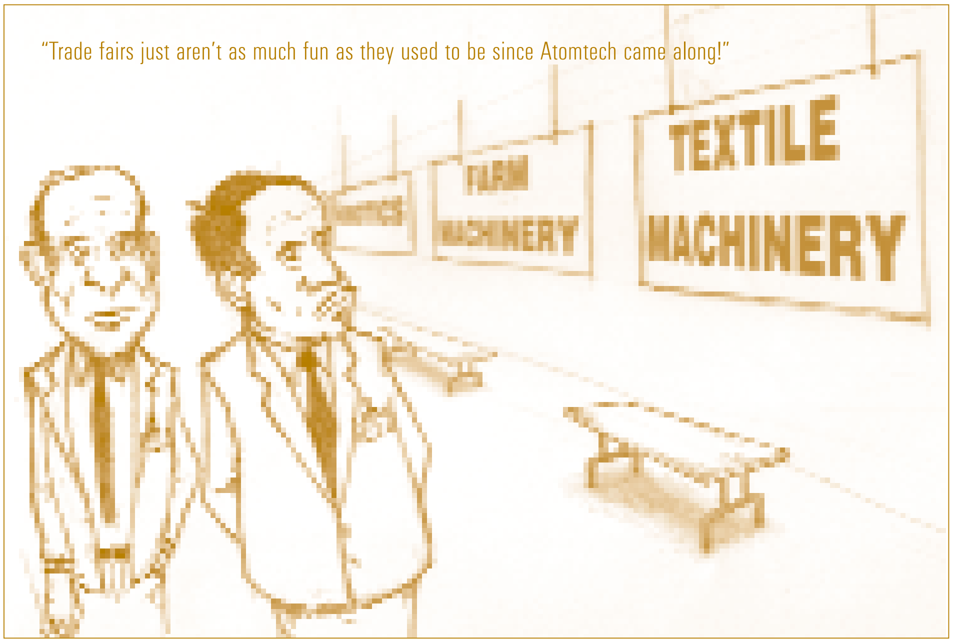
Raiders of the Last Ark?
The race is on to monopolize the elements of nature.

Atomtech won't stop at the nanoscale

HOW LOW CAN THEY GO? The word *atom* comes from the Greek meaning *not cut* and until late in the nineteenth century, it was believed that atoms were indivisible—the smallest components of matter. Now researchers know that an atom is made of hundreds of smaller particles, including the usual suspects we remember from high school chemistry—protons, neutrons and electrons. The structure of an atom looks like a swarm of electrons in the center of which is a densely-packed configuration of protons and neutrons (the nucleus). The number of protons in the nucleus determines which chemical element the atom will be. The more familiar atomic particles are accompanied by lesser-known particles called quarks and leptons (an electron is a kind of lepton) and a crowd of other particles called force carrier particles (with strange names such as gluon, graviton, Z Boson).[7] Quarks, which carry a fractional electrical charge (remember from chemistry class that protons carry a charge of +1, electrons carry a charge of −1 and neutrons have no charge?), are ten thousand times smaller than the nucleus of the atom. We don't know precisely how small quarks are, but we are sure they are smaller than 10^{-18} meters (a nanometer is 10^{-9} meters). Researchers think quarks are *literally* atomic–meaning that they are indivisible, not cut particles—but it may turn out that quarks are made up of still smaller particles. Mapping the sub-atomic realm in its entirety will be as useful to nuclear scientists as mapping the atomic world (i.e., the Periodic Table) was for chemists. As was the case with atom-level technologies, the first step to manipulating the sub-atomic cosmos is being able to see it clearly.

HOW FAST CAN THEY GO? Scanning probe microscopy, which allows us to "see" at the level of nanometers, isn't powerful enough to reveal what's happening in the nucleus of an atom. In order to take a peek at that dimension, nuclear physicists need a finer probe. The only one that fits the bill is another sub-atomic particle. In technologically-sophisticated chambers descriptively called accelerators (which are, in some cases, the size of large towns), scientists are able to push sub-atomic particles to speeds nearing the speed of light using electromagnetic fields. Once a particle gets up to speed, it gets smashed into the target particle, functioning as a probe. The collision is called an event, the details of which can be recorded by "detectors." Computers collect and organize the vast quantity of data from the detectors and present the results to the physicist. In addition to using accelerators to speed up sub-atomic particles in order to probe target particles, scientists can speed up particles and smash them into each other (these accelerator chambers are called colliders). The energy that is created from these collisions is converted into the formation of new massive particles whose properties can be studied. Using accelerators, scientists have identified dozens of elements (some of which are virtually non-existent outside of nuclear reactors or research labs).

WHY DO THEY GO? A definition provided by the US Department of Energy tells us that nuclear physics research seeks to understand the fundamental forces and particles of nature as manifested in nuclear matter.[8] But understanding the sub-atomic make-up of the universe is not a purely academic or cosmological investigation. Nuclear energy, nuclear weapons and nuclear medicine (including imaging using radioactive agents) all depend on our ability to carefully control (emphasis on *carefully*), to greater or lesser extents, the workings of the atomic nucleus. New sub-atomic technologies will be developed in tandem with a more precise understanding of the sub-atomic realm, exploding the possibilities for products that may dramatically affect our health and environment, for better or worse.



In the very near future, Atomtech could provide some of the following products:

- "Smart" fabrics that vary in their capacity to deflect or absorb heat
- Super-strong coatings for vehicles to reduce breaking and crumbling in collisions
- Lightweight bullet-proof armor in clothing for civilian, military and police use
- Maintenance-free building exteriors and break-proof glass and plastics
- Building surfaces that can "breathe" to admit or emit air flow
- Clothing and building surfaces that can change colour in response to environmental changes
- With the advent of large-scale "sheet" fabrication of nano-matter, we will see ships' hulls, airplanes and spacecraft with specialty "skins"

ELECTRONICS, ENERGY AND INFORMATICS

Nano-scale structures are expected to play a massive role in information and energy storage—two critical elements in almost any electricity-based product or process. Nano-scale technology is already responsible for the key component in the fabrication of hard disk drives. In addition, nanotubes have been shown to act as tiny transistors.[12] Late in August 2001, ibm researchers created a circuit capable of performing simple logic calculations via a self-assembled carbon nanotube. This was hailed as the first step toward nano-computers.[13] In May 2002, ibm reported that they have created carbon nanotube transistors that outperform models of even advanced silicon devices and outperform previously designed nanotubes with an increased capacity for carrying electrical current.[14] Prototypes of future nanotube computer chips should be coming out of the ibm labs in the next couple of years.[15] In sum, the potential includes:

- Data storage capacity and processing speeds will increase dramatically and be cheaper and more energy efficient. In June 2002 ibm's nanotechnologists demonstrated data-storage density of 1 trillion bits per square inch, equal to a 100-gigabyte hard-drive—or 20 times the data of the magnetic storage used in today's computers—enough to store 25 million printed textbook pages on a surface the size of a postage stamp. According to ibm fellow and Nobel laureate Gerd Binnig, "this nanomechanical approach is potentially valid for a thousand-fold increase in data storage density."[16]

- Biosensors and chips that could become ubiquitous in daily life—monitoring every aspect of the economy and society. For example, Nanomix Inc. is engineering nanotube-based sensors to detect dangerous gas leakages in chemical plants and refineries.[17] The company claims that each sensor will cost 10 times less than conventional gas detectors and will operate for a year on watch batteries;
- Reduced reliance on fossil fuels and hydro-electric power and their related infrastructure. Novel nanomaterials are being developed for hydrogen fuel storage, for example, an innovation that could dramatically increase the efficiency and decrease the cost of fuel cell cars.[18]

PHARMACEUTICALS AND HEALTH CARE

According to some enthusiasts, the sky is the limit.[19] ("We're gonna cure cancer… really!") The impact will be felt in medical devices and surgery (two-thirds of current research) and drugs (one-third). Within a decade, half of industry revenues (about us$180 billion per annum) will be based on Atomtech. Applications include:

- Faster genome sequencing with nano-scale biochips
- Precision characterization of an individual's genetic make-up
- New methods for drug delivery to targeted tissues or organs
- New vectors for gene therapy
- Surgical access to previously inaccessible body sites
- More durable and rejection-resistant artificial organs and tissue
- Lighter and "smarter" biomaterials for limbs
- Biosensing systems that will allow the detection of emerging disease at a much earlier stage

"Imagine the psychological impact upon a foe when encountering squads of seemingly invincible warriors, protected by armor and endowed with superhuman capabilities, such as the ability to leap over 20-foot walls."

Ned Thomas
Director of
the US Army's Institute
of Soldier Nanotechnologies[20]

MILITARY

Research on the military applications of Atomtech is a thriving business. The US Department of Defense is the second biggest recipient of US government funding for nanoscience research (after the National Science Foundation). In light of terrorist attacks and increased emphasis on technological-driven warfare, the commitment to Atomtech research for military uses is growing. In FY 2003, the US budget calls for us$201 million for Department of Defense spending on nanoscience—up from us$180 million in 2002. The following section describes just a few examples of non-classified research for Atomtech-enabled warfare.

In March 2002 the US Army created the 5-year us$50 million Institute for Soldier Nanotechnologies (isn) at the Massachusetts Institute of Technology.[21] Working with defense industry partner Raytheon, among others, the institute is conducting research on the use of Atomtech to improve soldier protection and survivability.[22] One of the primary goals is to enhance the performance of the individual soldier. Nano-equipped warriors of the future would have the ability to leap over 20-ft. walls (outfitted with shoes containing built-in power packs), fight with artificial limbs that are stronger than human muscles, wear uniforms that make them invisible, invincible and provide automated first-aid on demand. Using nanoscience, the Institute has the immediate goal of reducing the weight load of fully equipped soldiers from today's 145 pound cargo to 45 pounds. Inspired by medieval knights, the Institute is developing a "molecular chain mail" that is no heavier than paper. Additional military applications include:[23]

- Scratch-proof plastic nanocoatings for helmet visors and jet windows[24]
- The development of "exoskeleton" armor that is not only bullet-proof, but also transforms into a rigid medical cast to treat a broken arm or leg, or serves as a "forearm karate glove" to be used as an offensive weapon
- Nano-camo: Chameleon-like uniforms made of nanomaterials to make the soldier virtually invisible on the battlefield
- Nanoengineered materials to improve performance of gas masks
- Molecular scale "Venetian blinds" designed to protect soldier eyes from laser blinding
- Miniaturized sensors for field detection of biological/chemical/explosive warfare agents
- The use of super-strong, low-weight carbon nanotubes to manufacture missiles and other explosives
- Using nano-powered devices for unlimited availability of energy/power on the battlefield
- Longer-term goal of developing unmanned systems with mobility, control and self-awareness derived from living, biological systems
- University of Michigan researchers are exploring measures to counter biological warfare by preventing pathogens from entering the human body. The research seeks to develop a composite nanomaterial that will serve as a "pathogen avoidance barrier" and post-exposure therapeutic agent to be applied in a topical manner to the skin and mucous membranes[25]

Note: These examples barely touch the surface of military applications of Atomtech.

The potential use and proliferation of biosensors and technologies that enhance human performance will have profound consequences for human rights and democratic dissent. (See box on nbic, page 34 and etc Group *Communiqué*, "The New Genomics Agenda," September/October, 2001, *www.etcgroup.org*)

AGRICULTURE

Nano-fabricated detectors offer the potential to do thousands of plant experiments for simultaneous gene characterization and selection with very small amounts of material.[26] "Nano-chips" have been developed that have several thousand nanodots, each containing a small amount of different genes in a given plant and capable of determining the amount of that gene being expressed by the plant. When the gene-expression for tens of thousands of genes is tested and then compared, scientists can determine which genes are being activated or inhibited during the growing process or during disease. With the prospect of having in-hand complete genome sequences coupled with the nano-chips, the information will reveal which genes determine improved production or which genes are affected when a plant is exposed to salt or drought stress. Nano-chips will allow the genes to be completely characterized molecule by molecule in just a few hours. Less than ten years ago, this same analysis would have taken dozens of scientists years to complete.

In the longer-term (2020–2050), atomic-engineering could:

- Eliminate "geography" (photo-sensitivity, temperature, altitude) and labour as factors in crop production
- Eliminate "time" as a factor in food preparation (as energy and matter management become more efficient)
- Eliminate "agriculture" with non-biological food production (as nanobox manufacture of food from recycled elements becomes viable)

FOOD PROCESSING

The food and beverage industry is eagerly embracing Atomtech research. The food science department at Rutgers University (nj, usa) recently hired what it believes is the first "professor of food nanotechnology."[28] At Rutgers, Professor Qingrong Huang will focus on developing two applications of nano-scale technologies for the food industry: "nutraceutical" foods that will use proteins to deliver drugs to targeted areas of the body and food packaging that changes colour and alerts the consumer when the food inside starts to spoil.

In 1999, Kraft Foods, the us$34 billion food and beverage giant (subsidiary of Phillip-Morris), established the industry's first nanotechnology food laboratory. In 2000, Kraft launched the NanoteK consortium—involving an undisclosed amount of funding for 15 universities and national research laboratories to conduct basic research for tiny-tech innovations in food technology.

NANOCAPSULES: Kraft's NanoteK consortium is focusing on the development of personal food products that recognize an individual's nutritional or health profile—allergies or nutritional deficiencies—or even packaging smart enough to detect and alter the consumer's vitamin deficiencies.[29] The NanoteK researchers are also developing novel products that are tailored to each consumer's taste buds. For example, nanoparticles that encapsulate flavors, colours or nutritional elements could be activated on demand by zapping a liquid solution with a prescribed microwave frequency.[30] A thirsty consumer could buy a colourless and tasteless beverage from the grocery store and later select the flavor/nutrient/colour of her choice by setting a microwave transmitter to the correct frequency. The chosen nano-capsules would be activated while the others would remain dormant, releasing only the desired flavor, colour or nutrients.

SMART FOODS: Another food industry innovation is the addition of colour-changing agents on foods (or packaging) to alert the processor or consumer to unsafe food.[31] Using "electronic tongue" technology, sensors that can detect chemicals at parts per trillion, the industry hopes to develop meat packaging that would change colour in the presence of harmful bacteria.

"In our opinion, this is one technology [nanotechnology] that will have profound implications for the food industry, even though they're not very clear to a lot of people."

Jozef Kokini
Department Chair and Director of Rutgers' Center for Advanced Food Technology.[27]

NOT *IF* BUT *WHEN*

Atomtech is not a "maybe" technology. Those familiar with biotechnology's history will recognize the signs: in the '70s and '80s, conventional scientists took up a great deal of air time telling the world how many insurmountable, virtually impossible hurdles genetic engineering would have to overcome before it was commercialized. In arguing so, they ignored two realities:

- The development of biotechnology grew exponentially and in tandem with new computer (informatics) technologies that made genetic engineering faster and cheaper every day. Symbiotic and parallel processes will propel Atomtechnologies at a still more rapid rate.
- It is not necessary to get it right to get it to market. As the first generations of gm products make clear, failure in science can still mean success in business. Society (and the earth) will bear the burden of scientific blunders and government inaction. Ready or not, some sub-sets of Atomtechnology are commercially viable already.

SIX RECYCLABLE MYTHS

- **IT WILL FEED THE HUNGRY:** So far, biotech has fed the corporations. Most scientists believe that agricultural uses for Atomtech are a few decades away. If and when it arrives, the poor will be the last to have access and the first to lose jobs and markets.
- **IT WILL IMPROVE POOR PEOPLE'S HEALTH:** Not so far. Only if the poor eat too much, suffer from depression, or are going bald. Atomtech will be no more relevant to the needs of the poor—or accessible to them—than commercial biotechnology has been and, at least initially, will be more expensive.
- **IT WILL PROTECT THE ENVIRONMENT:** This was the theory that biotech's Generation One products would reduce chemical inputs. In reality, it has spawned a new generation of chemical dependency in agriculture.
- **IT'S A "GREEN" TECHNOLOGY:** Not that we've noticed. Atomtech, at best as a private good, will simply replace one set of environmental risks with additional and/or new problems associated with the manipulation of matter and of life, the control and regulation of nanoparticles, nuclear power and the management of possibly uncontrollable processes.
- **IT WILL SAVE LABOUR:** There is little evidence of this with biotech. Atomtech could well save labour but it will be the labour of the poor (miners, factory workers, farmers) who will become jobless and unable to afford Atomtech's products.
- **AT WORST, IT WILL NOT AFFECT THE POOR:** Although biotech has mostly been an oecd issue, its environmental and regulatory effects and its social implications have spilled quickly into the South. Biotech has influenced patent and trade policies in the wto with enormous disadvantage to the South. Biotech has leaked into the fields and food of the South even where it is forbidden and unwelcome. Biotech's Generation Three has the potential to displace or damage Third World workers and markets even if it is only used in the North.[32] The same "trickle-down trouble" will come with Atomtech.

It is myopic and naïve for Atomtech advocates to claim that a technology that the poor cannot control will somehow be used for their benefit.

ETC Evaluation

Civil society organizations with a history in biotech will experience an immediate and intense *déja vu* when they hear the claims that Atomtech will be a major benefit to the poor. As with biotech, it is theoretically possible that, in a just and gentle world, Atomtech could have a role to play. In the absence of such a world—as ever—the control of the technology will accrue to those with power and the commercialization of the technology will inevitably give them greater monopoly control.

It is worth recalling the biotech arguments and making the links to Atomtech...

Notes

1 Quoted in Ann Thayer, "Nanotech Meets Market Realities," *Chemical and Engineering News*," p. 17.
2 See footnote 1, Section 1.
3 Anonymous, "The Same—Only More So?," *The Economist*, December 8-15, 2001, p. 12.
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SECTION V

5

Even with all its unknowns, even with all its perils and risks, who'd say no to nano?

Ed Regis

Nano, the emerging science of Nanotechnology

WHO CARES?

The cast of characters addressing the new technologies

More than anything else, it is the diversity of institutional actors involved in Atomtechnologies that drives the enormous economic and political pressures rushing nano-scale science to market.

WHO CARES? NANO-NERDS: **Scientific Institutions**

As with biotech, the new set of technologies has been conceived and nurtured first in academia. Today, every major university purporting an interest in the physical sciences will also banner its innovations in Atomtechnologies. The range of colleges is interesting: mit, Max Planck Institute, Cornell, Rice University, University of California, Harvard and Cambridge are joined by smaller science centers at the University of Texas, Penn State, Uppsala University (Sweden), Kansas State, New York State, University of Washington (Seattle), and the University of Queensland (Australia)—to pick from the long list. During the 1990s, many of the Nobel Laureates in physics and chemistry won their prizes in atomic-scale research. (see chart, page 40).

WHO CARES? NANO-NICHERS: **Nano Start-ups**

Entrepreneurial profs move quickly these days from their university labs to nano start-up businesses. They often take their best ideas and students (and sometimes the ideas of their students) with them. Because—in these early days at least—it is hard to beat free access to campus laboratory equipment and student labour, many academics retain their university ties while they prepare to launch their first initial public offer (ipo)—to take a private company public on the stock market. Until that time, academics work closely with venture capital funds in order to amass the start-up cash they need. At least three US-based funds are now focusing exclusively on what they classify as "nanotechnology." The biotech boutiques of the '70s and '80s are now being replicated with the nano-nichers of the "Dot-Aught" decade. A sampling of players is described below (two of which made it onto the "Red Herring 100" for 2002—*Red Herring* magazine's ranking of companies "most likely to change the world").

A Sampling of "Nano-nicher" Companies

Company	What They Do
Argonide Nanometals Sanford, FL, USA www.argonide.com	Argonide manufactures nano-scale ceramic fiber materials to increase strength, support and insulation of metals, plastics, polymer-matrix and biomaterials. The company also produces aluminum nanopowders, used as accelerators, igniters or boosters in high-pressure rockets. In late 1999, Argonide received a US$1.4 million R&D grant from the Department of Energy, part of which pays to employ a number of scientists from the former Soviet Union previously involved in the development of weapons of mass destruction. The company is using novel nanomaterials to filter bacteria and viruses from drinking water.
California Molecular Electronics Corporation San Jose, CA, USA www.calmec.com	CALMEC aims to be a leader in the molecular electronics industry. Founded in March 1997 the company seeks to commercially develop the use of individual molecules to form the components of electronic devices.
Carbolex Lexington, KY, USA www.carbolex.com	Carbolex sells single-walled nanotubes (over the Internet, in bulk) to researchers in industry and academia. Carbolex is a member of the Advanced Science and Technology Commercialization Center at the University of Kentucky in Lexington, composed of both university faculty and scientists from high-tech corporations.
Carbon Nanotechnologies, Inc., Houston, TX, USA www.carbonnanotech.com	Carbon Nanotechnologies was founded by Bob Gower and Richard Smalley (1996 Nobel laureate and director of the NSF-funded Center for Nano-scale Science and Engineering at Rice University). The company produces, researches and sells carbon nanotubes using technologies licensed from Rice.
Chemat Northridge, CA, USA www.chemat.com	Founded in 1990, Chemat is devoted to the creation and commercialization of advanced materials and technologies using the company's proprietary technologies.
eSpin Technologies, Inc. Chattanooga, TN, USA www.nanospin.com	eSpin is the first commercial producer of 30–400nm diameter nanofibers with applications such as filtration, barrier fabrics, protective clothing, composites, tissue engineering and fuel cells.
Nanoframes LLC Boston, MA, USA www.nanoframes.com	Nanoframes' goal is to develop an enabling technology for the manufacture of functional nanoscale building blocks using self-assembling proteins. The company's motto is "harnessing nature to transform matter."
Nanomix Emeryville, CA, USA www.nano.com	Nanomix is pioneering the use of quantum modeling—the use of computers to virtually design nanomaterials atom-by-atom. The company's goal is to commercialize the first working nano components.

Company	What They Do
Nanolayers Jerusalem, Israel www.nanolayers.com	Founded in 2001, the company hopes to commercialize organic semiconducting materials using a technology developed by Dr. Shlomo Yitzchaik of the Department of Inorganic Chemistry at The Hebrew University of Jerusalem.
Nanophase Technologies Corp. Romeoville, IL, USA www.nanophase.com	With revenues of US$4.3 million in 2000, Nanophase is one of the few publicly-held nanotech companies. The company uses a patented process to engineer the physical, optical, electrical and mechanical properties of nanomaterials that can be added to other materials in order to increase strength, abrasion resistance and electrical conductivity. Nanophase produced 200 metric tons of nanomaterials in 2000 and has applied for 29 patents covering key technologies.
Nanoprobes Yaphank, NY, USA www.nanoprobes.com	Nanoprobes produces and sells nano-sized gold colloid particles used in bio-diagnostics, including disease-detection and pregnancy tests.
Nanosphere, Inc. Alachua, FL, USA www.nanosphere.com	Nanosphere, founded by University of Florida researchers, focuses on commercializing technologies that use nanoparticles in inhalation therapies.
Nano-X GmbH Saarbrücken-Güdingen, Germany www.nano-x.de	NANO-X GmbH uses chemical nanotechnology to develop and produce new materials with multi-functional characteristics such as self-cleaning surfaces, anti-graffiti walls and scratch-resistant plastic.
Quantum Dot Corporation Hayward, CA, USA www.qdots.com	Quantum Dot uses semiconducting nanocrystals ("quantum dots") for biological, biochemical and biomedical applications. Quantum dots, attached to biomolecules, act as optical beacons that light up in different colours depending on their size. QD has raised over US$37.5 million in financing and has applied for over 50 patents.
Semzyme Santa Barbara, CA, USA www.semzyme.com	The start-up founded by Angela Belcher and Evelyn Hu aims to commercialize "protein tools" that can be used as nanoscale wiring for electronic components.
Sustech GmbH Darmstadt, Germany www.sustech.de	Founded by a group of six professors, the company's lab is based in the chemistry department of the Darmstadt University of Technology. Sustech's goal is to develop environmentally sound products using nano-scale systems.
Zyvex Corporation Richardson, TX, USA www.zyvex.com	The first and only company devoted solely to the development of molecular manufacture technology. Zyvex is developing manufacturing architectures for miniature robotic arms, working together to assemble miniature parts.

WHO CARES? ATOMTECH GIANTS: **Multinational Matter Moguls**

Diverging from the pattern of biotech's history, the Atomtechnologies have attracted the interest of the big multinationals from the beginning. Whereas bio-boutiques cried out in the wilderness as predatory corporate giants lurked menacingly just over the horizon, some of the world's largest companies have already understood that the BIG *Down* will wait for no one. ibm has already committed us$100 million to research and development on nanoelectronics.[1] Since the new technologies manhandle every segment of the global marketplace, the range of corporations involved is no less diverse. Exxon Mobil, ibm and Dow Chemical are joined by Xerox, 3M and Alcan Aluminum. The Americans also have Johnson & Johnson, Hewlett-Packard, Lucent, Motorola, Eli Lilly and DuPont. The Japanese have strong contenders in Sony, Toyota, Hitachi Mitsubishi, nec and Toshiba. The Europeans have Philips, L'Oreal, Aventis, basf and Bayer as well as a cadre of smaller Scandinavian, French and Dutch enterprises. The reasonable operating assumption is that these companies rule the roost.

A case in point was the flurry and fuss over nano-scale plastic catalysts (see above, p. 48) in which more than 3,000 patents were granted to a horde of companies. After the dust settled, Exxon Mobil and Dow walked away with technological control. The winning combination was litigation and love. Those they couldn't intimidate with lawsuits they simply absorbed.[2]

WHO CARES? NANO-CRATS: **Government Backers**

The largest visible backing for the new technologies, of course, comes from governments. As of mid-2002, at least 30 countries had initiated national activities in nanosciences. The National Nanotechnology Initiative announced by US President Bill Clinton in January 2000 trumpeted the beginning of a neck-and-neck race for power between the usa and Japan with the European Union trying hard to catch up. Here's where they stand now…

"Every nation in the world is looking at nanotechnology as a future technology that will drive its competitive position in the world economy."

Neal Lane
Rice University
Physics Professor[3]

Japan While the United States may be seen as the birthplace of theoretical Atomtechnology (marked by Richard Feynman's now-famous address to the American Physical Society at Caltech in 1959), Japan could be said to have given birth to applied Atomtechnology when nec researcher Iijima Sumio discovered carbon nanotubes in 1991. At present, Japan is focused on economic recovery and the government is convinced that science and technology hold the key to that recovery. Accordingly, the budget for science and technology R&D is being increased even while the budgets of most other governmental departments are being slashed. Increased government funding for nano-scale science research began back in 1995 with the passage of Japan's Science and Technology Basic Law No. 130, resulting in an overall increase of public support for basic research.[4] The law allocated approximately us$14.8 billion for basic research to universities, industry, and national laboratories from 1996 to 2000. In March 2001, the government announced that the next 5-year investment (2001–2005) would increase to us$20.8 billion).[5] For the single year 2001, the government allotted us$431 million for nano-related science.[6] Government organizations and very large corporations are the main source of funding for Atomtechnology research and development in Japan. All large Japanese corporations devote a significant portion (generally ~10% in the electronics industry) of their income to R&D. Japanese corporate research tends to be product-oriented, but there is also a well-established culture within the corporate and scientific community of planning for the next generation of technological innovation.

The main government organizations sponsoring nanotech in Japan are the Ministry of International Trade and Industry (miti), the Science and Technology Agency (sta), and Monbusho (the Ministry of Education, Science, Sports and Culture).

Often in association with the government, large corporations are bank-rolling nanotech in Japan, particularly Hitachi, nec, ntt, Fujitsu, Sony, Mitsubishi. In 2001, the Mitsubishi Corporation launched the world's first nanotechnology private equity fund called Nanotech Partners. The us$100 million fund now supports Frontier Carbon Corporation, a bulk-producer of fullerenes.[7]

Private consortia are also playing a major role in Japan. In addition, university-industry interaction is stimulated by miti projects awarded to universities that encourage temporary hiring of research personnel from industry. Many of the academic labs are staffed with long-term visitors from industry. A single lab may have workers from competing industries, working side-by-side on company-specific projects.

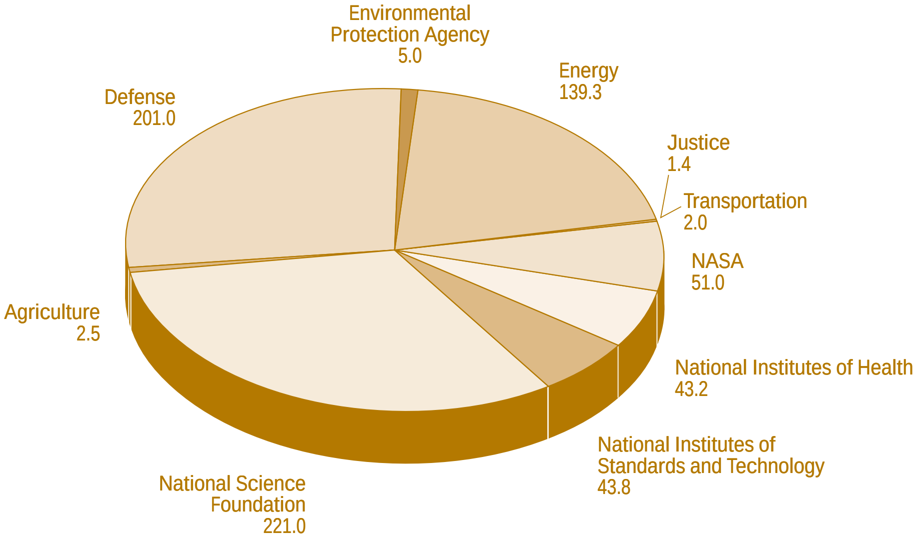
U.S.A. Japan's early strides in Atomtechnology provided the motivation for the usa to launch its National Nanotechnology Initiative.

US federal agencies spent $116 million on nanotech research in 1997, with the National Science Foundation bearing the bulk, spending $65 million. A July 2000 report prepared by the National Science and Technology Council's Subcommittee on Nano-scale Science, Engineering and Technology proposed the National Nanotechnology Initiative, which increased the amount of investment by over one and a half times from the previous year.

Bill Clinton requested $495 million for nanotech research for fy (fiscal year) 2001 and received $422 million from Congress, to distribute among six government agencies: National Science Foundation (receiving the largest share), Department of Defense, Department of Energy, National Institutes of Health, National Aeronautics and Space Administration, and the Department of Commerce's National Institute of Standards and Technology. George W. Bush asked for $518.9 million for Atomtech research for fy 2002 and six additional government agencies were slotted to receive nni funds for the first time. The new recipients were the Departments of Agriculture, Justice, Transportation, Treasury, State, and the Environmental Protection Agency. For fy 2003, Bush wants to increase funding for the National Nanotechnology Initiative to $710 million and some influential members of the us Congress have introduced a bill called the "Investing in America's Future Act" that would increase Atomtechnology spending within the National Science Foundation in 2003 from $221 million to $238 million.[8]

In September 2002 a bill was introduced in the us Congress to create a new, permanent federal agency to promote nano-scale science, R&D and education. The bill would establish the National Nanotechnology Research Program, a federal agency

US Government Nanotech Funding by Department, FY 2003
Total: $710.2 Million



Figures are in US$ millions
Source: M.C. Roco, National Science Foundation

with its own budget and staff, presumably making nano-scale research less dependent on the mood of the White House. The Congressional hearing on the proposed bill was described by the *Small Times* trade journal as a "nanotechnology love-in."[9] The bill provides $5 million per year for a new center for ethical, societal, educational, legal and workforce issues related to nanotechnology.

The US government is assuming that large transnational corporations are investing in Atomtech at levels comparable to its own financial commitment. Small nano-startups are supplying researchers with nanomaterials. Semiconductor processing consortia, such as Sematech (a consortium of 13 semiconductor manufacturing corporations from 7 countries, headquartered in Austin, tx) and the Semiconductor Research Corporation (a consortium of members from university and industry with headquarters in Research Triangle Park, nc and San Jose, ca) are contributing to the research. Interdisciplinary centers with Atomtechnology activities have been established in the last few years at many US universities and, in 2000, the University of Washington launched the first US doctoral program in nanotechnology.

European Union The eu's investment in nanotechnology is particularly difficult to assess because in addition to national programs, large corporations, universities and consortia, there are collaborative networks that include a few or several countries:

Examples include:

- The phantoms (Physical and Technology of Mesoscale Systems) program is a network created in 1992 with about 40 members based in Leuven, Belgium.
- The European Science Foundation's network formed in 1995 for Vapor-phase Synthesis and Processing of Nanoparticle Materials (nano). This consortium bridges between the aerosol and materials science communities working on nanoparticles and includes 18 research centers.
- The European Consortium on NanoMaterials (ecnm) was formed in 1996 and is centered in Lausanne, Switzerland.
- neome (Network for Excellence on Organic Materials for Electronics) which has had some nano-related programs since 1992.
- The European Society for Precision Engineering and Nanotechnology (euspen) was designed in 1997 with participation from industry and universities from six EU countries.
- The Joint Research Center Nanostructured Materials Network was established in 1996 and is centered in Ispra, Italy.

EURO FUNDING: The Sixth Framework Programme, the primary instrument for the funding of science and technology research in the European Union, was adopted in mid-2002. The programme emphasizes nano-scale sciences as one of seven key funding areas, devoting us$1.3 billion of its 2002–2006 budget to nanotech, twice the amount committed to nanotech in the previous funding round.[10] cordis, the European Commission's Research and Development Information Service, maintains a web site with details on the Sixth Framework Programme (2002–2006).

NATIONAL NANO IN EUROPE: Germany, France, Switzerland and the UK have particularly well-established national Atomtechnology research programs. Switzerland is spending us$72 million on nanotech—the world's highest per capita investment in nano-scale science initiatives.[11] In Germany, the Federal Ministry of Education, Science, Research and Technology (Bundesministerium für Bildung und Forschung-bmbf) has established six "Centers of Competence in Nanotechnology" throughout the country. The competence centers are focused on the industrial application of Atomtechnology; their functions are "mainly public relation, education and teaching, creation of an economically attractive environment and the counseling of mainly industrial prospects in the corresponding field of nanotechnology." In mid-2002 the German Ministry for Education and Research launched a new, us$50 million nanobiotechnology support program over 6 years.

The Fraunhofer and Max Planck Institutes (particularly the Max Planck Institute for Solid State Research, Stuttgart, and the Max Planck Institut für Biochemie, Martinsried) have also formed centers of excellence in the field of Atomtechnology research.

The United Kingdom plans to devote us$43 million for new interdisciplinary research on nanotech over the next six years and us$70 million for a nanotech Business and Science Park at Oxford University.[12]

France's Center National de la Recherche Scientifique (cnrs) has developed research programs on nanoparticles and nanostructured materials at about 40 physics laboratories and 20 chemistry laboratories throughout the country. Although France is a relatively small player, the government hopes to expand nanoscience research. France has five main nanotech research centers with **clean room** facilities and there are an estimated 1,000 researchers in nanoscience and 1,000 doctorates and postdoctorates working in the field.[13]

Australia Australian capacity in nano-scale science is centered primarily within public sector research institutions, especially the Commonwealth Scientific and Industrial Research Organization (csiro), Cooperative Research Centres and universities.[14] In January 2002 the government announced that its Australian Research Council would devote a third of its 2003 budget (about us$86.4 million over five years) to four priority areas including nanotechnology, genomics, complex and intelligent systems and photonics. The nanotechnology funding includes support for the expansion of the Semiconductor Nanofabrication Facility at the University of New South Wales into a Special Research Centre for Quantum Computer Technology. In December 2001 the University of Queensland and the Queensland government announced that they would establish an Australian Institute of Bio-Engineering and Nanotechnology at the Queensland campus in Brisbane.[15] Four universities—New South Wales, Queensland, Western Australia and Sydney—announced in November 2002 that they would collaborate to buy and share four powerful electron microscopes.[16] The collaboration is sponsored by the Nanostructural Analysis Network Organization Major National Research Facility based in Sydney.

WHO CARES? SOUTH NANOS

Research on nano-scale technologies is also underway throughout the South. Beyond the obvious high-tech leaders in Asia and the Pacific a handful of countries are establishing nano-scale science initiatives and are determined that their countries not be excluded. The vast majority of work in Latin America and Africa appears to be based in universities or scientific institutes, with only minimal government support. Outside of a handful of countries in each region, Atomtech remains at a very nascent phase in most areas of the South, with very little activity in Africa thus far.

The map on page 66 illustrates the number of atomic force microscopes found in select countries as of mid-2002. It gives one measure of the South's technical capacity relative to industrialized nations. The map is based on information provided by Veeco, the world's largest seller of atomic force microscopes. However, it is a single indicator of nanoscience capacity at one point in time, and is not a complete or definitive picture.

Similarly, our review of nanoscience initiatives in the South is by no means complete or comprehensive. The following are among the earliest and most prominent Atomtech participants in the South:

Taiwan In September 2002 the government of Taiwan launched a six-year, us$667 million investment to promote nanotech applications.[17] Also in September 2002, the Cabinet-level National Science Council (nsc) inaugurated a nanotechnology laboratory and chip system design center in the Taiwan Science-based Industrial Park. The nsc earmarked us$1.1 million for the implementation of the project.[18] Taiwan is home to several companies producing nanoparticles, including China Synthetic Rubber Corp., United Silica Industrial Ltd., DuPont Taiwan Ltd., Eternal Chemical Co., Ltd. and Pai Kong Ceramic Materials Co., Ltd.[19] It is projected that Taiwan's Atomtechnology industry will be worth us$8.69 billion in 2008, with more than 800 manufacturers involved in related investment, research and production.[20] In June 2002, Taiwan's minister of economic affairs, Lin Yi-fu, led a 30-person delegation to Germany, Britain and Spain to drum up investment in all of Taiwan's hi-tech industries.[21]

South Korea South Korea is gaining prominence in the field of nano-scale sciences. In March 2002 the South Korean government announced plans to invest us$145 million in nanotech—a 93% increase from 2001. South Korea's Ministry of Science & Technology will build a nanofabrication center at the Korea Advanced Institute of Science & Technology. The government also plans to offer tax incentives to foreign companies for Atomtech research.[22]

Peoples Republic of China According to Bai Chunli, vice president of the Chinese Academy of Science, the government of China has invested only modest amounts in nanotech research.[23] Nonetheless, to the dismay of Taiwan and Japan, China attracts high-tech companies from neighboring countries looking for lower production costs. Even without a major financial commitment from the government, China has made impressive strides in research related to nanotubes. China's nanotech development is centered around Shanghai, which hosts a cluster of twenty nanoscience related institutions.[24] China's National High Technology Research and Development Program aims to enhance China's international competitiveness and improve the nation's overall R&D capability in high technology.[25] The program has funded projects such as the Chinese Academy of Sciences' hydrogen storage carbon nanotube program. The Center for Nanoscience and Nanotechnology at the Chinese Academy of Sciences in Beijing opened in 2000. The center joins more than a dozen institutes and universities in the hinterlands of China to collaborate on research.[26] In September 2002, Veeco Instruments Inc. established a China Nanotechnology Center facility (cnc) in Beijing. The facility is to be staffed by local scientists and engineers and equipped with the company's atomic force microscope and scanning tunnel microscope. The facility will be operated jointly with the Institute of Chemistry of the Chinese Academy of Sciences, a national research organization.[27]

Singapore The government of Singapore budgeted us$36.7 million on nanotechnology initiatives from 1997-2002 and is enthusiastically promoting Atomtech business.[28] In January 2002 the Nanoscience & Nanotechnology Initiative (nusnni) was established at the National University of Singapore. nusnni is an interdisciplinary group composed of faculties from the departments of electronic engineering, mechanical engineering, material engineering, environmental engineering, chemistry, physics, biology, mathematics and others. In March 2002 Singapore also established the Institute of Bioengineering that conducts joint research with SurroMed Inc. (US) in nanobiology.

India Indian research on nanomaterials is still in a "nascent phase."[29] The Indian government has not yet provided substantial funding for nanoscience initiatives. The most prominent Atomtech research is concentrated in fewer than a dozen publicly-funded institutions. Among the most prominent are: the Indian Institute of Science in Bangalore, the Tata Institute of Fundamental Research, the iits and Radiophysics Institute of the University of Calcutta.[30] Surprisingly, there is little industry activity to date, although several leading pharmaceutical companies in India are reportedly investing in nanoparticle projects for drug delivery.[31]

Mexico Scientists in Mexico are eager to obtain government support for Atomtech research, which is now confined to a handful of leading scientific institutes. These include the Instituto Nacional de Investigaciones Nucleares (inin), the Centro de Investigación Científica y de Estudios Superiores de Ensenada (cicese) and the Instituto Potosino de Investigación Científica y Tecnológica (ipicyt). ipicyt researchers, Humberto Terrones Maldonado and Mauricio Terrones Maldonado are among the world's most prominent scientists conducting research on the use of electron beam welding to connect carbon nanotubes.[32] Their laboratory in San Luis Potosí is equipped with a highly sophisticated electron microscope, which is the only one of its kind found in Latin America.[33]

Brazil In 2002 the Brazilian government invested about us$1 million in research to promote nanotech initiatives.[34] Centers are being established in São Paulo, Paraná, Minas Gerais and Pernambuco states, and there are collaborative programs with France, Germany, The Netherlands and the usa. Atomtech research in Brazil is structured in four networks involving more than 200 Ph.D.s throughout the country. The networks include the following areas of research: 1) nanoelectronics and related areas; 2) nanostructured materials; 3) molecular nanotechnology; and 4) nanobiology.[35]

South Africa The South African Nanotechnology Initiative (sani) was launched in March 2002, although comprehensive funding is not yet available from the government.[36] The aim of sani is to promote nanotechnology research and applications at all levels of government and industry in South Africa. A primary focus is on the use of nano-materials and nanoparticles related to the mining industry. As the world's largest producer of platinum and gold, there is particular interest in the use of nanotech to improve the design uses of minerals. According to a recent survey, there are five atomic force microscopes in South Africa.

A MEASURE OF NANOSCIENCE CAPACITY IN THE SOUTH

Veeco Metrology accounts for almost 90% of the world market in the manufacture and sale of high resolution Atomic Force Microscopes (afm) and new Scanning Probe Microscopes (spm). These sophisticated tools have become the "research standards" for atomic imaging and molecular measurements. The price of a basic Atomic Force Microscope is approximately us$175,000.

Distribution of Atomic Force Microscopes in the World

Source: Digital Instruments, a division of Veeco Metrology. *Information on South Africa obtained from South African Nanotechnology Initiative.

WHO CARES? NANO-WATCHDOGS: **Civil society groups monitoring new technologies**

The list of civil society and other nongovernmental organizations monitoring Atomtechnologies is not long. This is not to say that many groups do not have open files on the technologies but few have published information and fewer still have social action strategies. This will change. Some of the current actors are briefly described here:

ETC Group The etc Group (formerly known as rafi) is an international civil society organization based in Winnipeg, Canada. etc Group (pronounced et cetera) is dedicated to the conservation and sustainable advancement of cultural and ecological diversity and human rights. To this end, etc Group supports socially responsible developments in technologies useful to the poor and marginalized and it addresses governance issues affecting the international community. etc also monitors the ownership and control of technologies, and the consolidation of corporate power. etc Group's publications are available on the web site.
www.etcgroup.org

Foresight Institute The Foresight Institute, established by nanotech guru, K. Eric Drexler and directed by Christine Peterson, is based in Palo Alto, California. The Institute is the oldest source of broad social and scientific commentary on the potential impact of Atomtechnologies. Although decidedly pro-nano, the Foresight Institute does warn about both the intellectual property and environmental issues surrounding the new set of technologies. (For additional information, see "Nano-Net" in "Sources and Resources" of this report.)
www.foresight.org

The International Center for Bioethics, Culture and Disability The Center's web site provides a wealth of information on bioethics and disability, including numerous links and documents pertaining to Atomtechnology. Dr. Gregor Wolbring, a biochemist at the University of Calgary and founder of the Center, has authored numerous papers and offers a much-needed critical analysis of the application of Atomtech and converging technologies for "enhancing" human performance. Wolbring warns that the emphasis on human performance enhancement is driven by the quest to use technology to treat or eradicate what is perceived as human "defects" rather than addressing the need for social solutions—acceptance, respect and human rights. Dr. Wolbring's articles are among the most important contributions to the US government's controversial draft report on human performance enhancement.

The Center aims to:

- examine the cultural aspects of bioethical issues and of science and technology
- examine the impacts of bioethical issues and of science and technology on those who have been marginalized
- ensure that those who have been marginalized have a voice in all the debates that affect their lives
- help those who have been marginalized participate in the debates that affect their lives from a position of strength and knowledge
- raise the capacity of those who have not been marginalized to welcome and understand the views of those who have been

www.bioethicsanddisability.org

The Institute for Science in Society Founded in 1999, the Institute of Science in Society (isis) is a not-for-profit organization based in London that works for social responsibility and sustainable approaches in science. isis promotes critical public understanding of science and seeks to engage both scientists and the public in open debate and discussion. The Executive Director of isis, Dr. Mae Wan Ho, has authored several papers offering critical analysis of Atomtechnology. All of the isis publications are available on the isis web site.
www.i-sis.org.uk

The Science and Environmental Health Network (SEHN) Founded in 1994 by a consortium of North American environmental organizations, sehn is concerned with the wise application of science to the protection of the environment and public health. sehn is the leading proponent in the United States and Canada of the precautionary principle as the basis for environmental and public health policy.
www.sehn.org

Notes

1 According to Ed Niehaus, Consultant, Foresight Conference, October 10, 2002.

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SECTION VI

6

Nanotechnology
has given us
the tools...to
play with the
ultimate toy box
of nature—atoms
and molecules.
Everything is
made from it...
The possibilities
to create new
things appear
limitless.

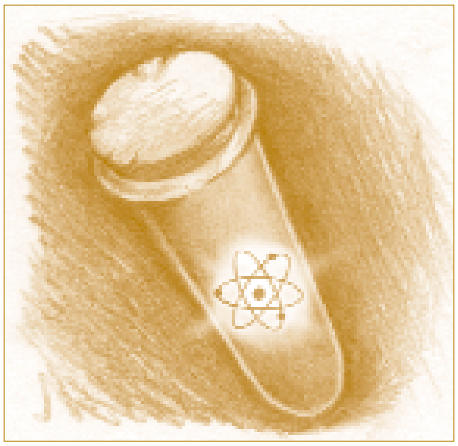
Horst Störmer
1998 Physics
Nobel Prize Winner[1]

CONCLUSIONS AND POLICY RECOMMENDATIONS

OUR CONVERGING FUTURE

The realm of nanoscience is utterly unimaginable to most of us, but the dawn of Atomtech is no small matter.

Atomtech's arrival is enormously significant because it gives us unprecedented potential to control and manipulate all matter—living and non-living. Atomtech is the great enabler—it offers access to a new realm, a molecular playing field where the building blocks for powerful technologies converge. Once we have the tools to precisely control and manipulate matter, we're positioned to exploit and integrate technologies, including biotechnology, informatics, cognitive sciences and more.



etc Group's analysis reveals that, even in today's fickle financial climate where hi-tech stocks are spurned by jilted investors, Atomtech is gaining a critical mass of investment, innovation and hype that is propelling nanoscience into a real and viable technology in the marketplace.

We find:

- The tools that allow us to exploit Atomtechnology—to see and manipulate nano-scale materials—are advancing rapidly
- Globally, billions of dollars are pouring into basic research. Over 30 national governments have launched nanoscience initiatives, and more will follow
- An impressive range of Fortune 500 companies is beefing up in-house R&D related to Atomtech
- Atomtech entrepreneurs are launching start-ups and venture capitalists are signaling interest
- The number of nano-related scientific articles and nano-related patents is surging

Atomtech boosters tell us that we are on the cusp of a new industrial revolution—a new economy of manufacture that has the potential to change the way we live, eat, work, wage war and define life. According to some industry advocates, Atomtech will trigger a new economic renaissance that combines the dream of material abundance, sustainable development and profit.

But history suggests a different scenario. In recent decades we have witnessed the privatization of science and a staggering concentration of power in the hands of giant multinational enterprises. In the more distant past, industrial revolutions have, at least initially, increased poverty. Given this reality, it is critical to ask: Who will control Atomtech? Who will determine the research agenda and who will benefit from converging technologies? How can civil society and governments begin to address the potential socio-economic, environmental and health impacts of Atomtech without discouraging the safe exploration of its beneficial possibilities? Because history affords us few clues and no working models, civil society must take the lead.

CONVERGING CSOs: Nano-scale manipulation is the unifying force for converging technologies. Might it also provide a unifying platform from which civil society can understand and address converging technologies? The atomically-modified economy of the future offers common ground for advocates and activists in the fields of biotech, toxics, public health, workers' rights, food security, sustainable agriculture, disability rights, alternative energy, anti-nuclear and opponents of chemical, biological and nuclear weapons, among others. All these areas are potentially affected by nano-scale manipulations. Efforts to understand and address Atomtech will require the participation (and cooperation) of diverse organizations and communities.

MOVING FORWARD: The Precautionary Principle offers a simple and commonsense approach to Atomtechnology. The Precautionary Principle says that governments have a responsibility to take preventive action to avoid harm to human health or the environment, even before scientific certainty of the harm has been established. Under the Precautionary Principle it is the proponent of a new technology, rather than the public, that bears the burden of proof. While the Precautionary Principle has gained considerable acceptance, especially in Europe, it is not universally defined or embraced.

To implement a precautionary approach, civil society and governments must begin to formulate the legislative, regulatory and social framework necessary to guide the assessment—and where appropriate, the introduction—of new technologies. This process must be transparent, democratic and involve those who are potentially adversely affected by new technologies. Unfortunately, these conditions do not exist today.

Therefore, etc Group makes the following policy recommendations:

- Regulatory bodies in oecd countries have thus far established no policies or protocols for considering the safety of Step 1 Atomtechnology, which includes nanoparticles in products already on the market and new forms of nano-scale carbon. At this stage, we know practically nothing about the potential cumulative impact of human-made nano-scale particles on human health and the environment. Given the concerns raised over nanoparticle contamination in living organisms, etc Group proposes that governments declare an immediate moratorium on commercial production of new nanomaterials and launch a transparent global process for evaluating the socio-economic, health and environmental implications of the technology.
- In the future, the specter of molecular manufacturing poses enormous environmental and social risks and must not proceed—even in the laboratory—in the absence of broad societal understanding and assessment.
- Emerging technologies require scientific, socioeconomic and societal evaluation in order for governments to make informed decisions about their risks/benefits and ultimate value. To this end, etc Group proposes the development of an International Convention for the Evaluation of New Technologies (icent). There is equally a need to develop mechanisms for the evaluation of emerging technologies at the national and local levels that will empower citizens to participate in open, informed debates.

- In the early 1990s, the United Nations System lost its capacity for the effective monitoring of multinational corporations and competent assessment of new technologies. The UN Centre on Transnational Corporations was disbanded and the UN Centre for Science and Technology for Development was gutted. The loss of these two vital but undervalued agencies was tantamount to a frontal lobotomy for the intergovernmental community and for the South, in particular. During the '90s, global corporate mergers rose sevenfold (soaring from under half a trillion dollars per annum to us$3.4 trillion) and high-tech stocks jumped sixfold (growing from 5% to 30% of stock values) during the greatest technology boom since the ipo for The Garden of Eden. etc Group recommends that the UN General Assembly establish a new "UN Centre on Commerce and Technology" with a wider mandate and the necessary resources to monitor, report and advise on corporate power in the context of both technologies and markets with particular reference to societal impacts.

ETC Evaluation

Laws of Technology Introduction

1 It takes a full human generation to comprehend the ramifications of a new technology. Therefore, decisions about whether or not or how to use a new technology will necessarily be ambiguous. Society must be guided by the Precautionary Principle.

2 In evaluating a new technology, the first questions must be: Who owns it? Who controls it? By whom has it been designed and for whose benefit? Who has a role in deciding its introduction (or not)? Are there alternatives? Is it the best way to achieve a particular goal? In the event of harm, with whom does the burden of liability rest and how can the technology be recalled?

3 The extent to which a new technology may be beneficial to society will be in proportion to the participation of society in evaluating the technology—including and especially those people who are most vulnerable.

4 A new technology cannot definitively be assessed as "positive," "negative" or "neutral," although certain technologies—in an equitable environment—may be intrinsically decentralizing, democratizing and helpful.

5 For every so-called "Luddite" attempting to establish social controls over the introduction of a technology, there is a powerful elite using social controls to impose new technologies on society.

6 The introduction of a new technology is not inevitable.

7 Any new technology introduced into a society that is not itself a just society can exacerbate the gap between rich and poor—and may even directly harm the poor.

8 A new technology cannot be a "silver bullet" for resolving an old injustice. Hunger, poverty, social disablement and environmental degradation are the consequences of inequitable systems—not of inadequate technologies.

9 The leaders of a society who permit injustice are the least likely to introduce a new technology that will correct injustice.

Notes

1 Cited in "Nanotechnology: Shaping the World Atom by Atom," available on the Internet: www.nano.gov

SOURCES AND RESOURCES

APPENDIX A:

Nano-Net

www.apnf.org

The Asia Pacific Nanotechnology Forum (apnf) is a networking organization focused on Atomtech development in Pacific Rim countries. Its stated purpose is to facilitate information flow between nanotechnology developers and investors and to facilitate the coordination of programs and cross-regional collaborations among government policy makers, industry and leading R&D institutions. apnf hosts the annual Forum Conference and holds quarterly Nanotech Briefings for Forum members. Each meeting takes place in a different city in the Asia Pacific region. apnf also produces a quarterly newsletter. apnf is supported by governments and industry. apnf is a membership organization (membership fees range from us$120 for individuals to us$5000 for corporations), but being part of the apnf community "means you rub shoulders with the world's most influential Nanotechnology leaders," according to the Forum's web site. There are useful postings about Asia Pacific-related Atomtech news and events accessible to non-members.

www.acronym.org.uk/dd

Disarmament Diplomacy, published since January 1996, is the successor journal to *Nuclear Proliferation News* and is available on-line. The journal, now being published by the Simons Center for Peace and Disarmament Studies at the Liu Institute (Vancouver, Canada), disseminates critically important research and analysis on the dangers of using Atomtechnologies to either enhance existing weapons of mass destruction (wmd) or to develop a new category of wmd. The July/August 2002 issue of *Disarmament Diplomacy* featured an article entitled, "Nanotechnology and Mass Destruction: The Need for an Inner Space Treaty," which urged the international community to adopt a Treaty to protect the planet from devastation caused by artificial and molecular structures. The October/November 2002 issue featured an article about US research on the use of Atomtechnologies to develop fourth-generation nuclear weapons.

www.foresight.org

Foresight is a nonprofit organization, founded by K. Eric Drexler and Christine Peterson, with the mission to help prepare society for future nanotechnologies. Since 1989, the *Foresight Institute* has sponsored conferences on nanotech, focusing especially on molecular manufacturing. An on-line archive is available for the 2000–2001 Foresight Conferences. Foresight publishes a quarterly newsletter, the *Foresight Update*, relating both technical and non-technical developments in Atomtechnology. The *Update* is available on-line and is intended for a wide audience. Foresight also maintains a news and discussion web site, *www.nanodot.org*, and runs the Institute for Molecular Manufacturing (imm), *www.imm.org*, a nonprofit foundation formed in 1991 to carry out research that furthers molecular manufacturing technologies. imm also promotes guidelines for research and development practices that are intended to minimize risk from accidental misuse or from abuse of molecular nanotechnology. The Foresight Guidelines on Molecular Nanotechnology, available at *www.foresight.org/guidelines/current.html#Principles*, make for powerful reading as suggestive and specific indications of the possible hazards involved in research related to self-replicating nanomachinery.

www.nano.org.uk

The Institute of Nanotechnology (ion) is a registered charity in the United Kingdom. It was established in 1997 "to provide a focus for the burgeoning interest in nanotechnology, encourage new research and keep the public aware of developments in the field." The majority of the activities of the Institute take place through its web site, where information related to technological developments, conferences, seminars and other international events is posted. Members receive a regular Atomtech bulletin by electronic mail. The most interesting features of the site (e.g., company case studies, country-by-country reports) are restricted to "Professional" and "Corporate" Members, but membership at the "Associate" level is free.

www.nano.gov

The web site of the US government's National Nanotechnology Initiative provides important information on government spending on Atomtech, including budgets for individual government agencies. Under the heading "Information on R&D," there is a link to the Nanotechnology Database, *itri.loyola.edu/nanotechnology_database*, which is operated from Loyola College in Maryland. This "nanobase" is perhaps the most comprehensive US Atomtech resource site on the Internet, providing links to major research centers, funding agencies, major reports and books. It also provides a link to a government-authored introductory brochure intended for a lay audience, in pdf format: *www.wtec.org/loyola/nano/IWGN.Public.Brochure*

www.nanoapex.com

NanoApex supports the development of two emerging technologies, nanotechnology/mems and Artificial Intelligence. NanoApex is a media and research company that provides current news, information about research and other resources related to Atomtech on its web site. NanoApex bought the Atomasoft Corporation (with the spooky but prescient motto "matter will become software") in August 2002. The NanoApex web site provides links to an image gallery, to a glossary and to information about Atomtech-related books, events and companies. Nanoapex also owns *NanoInvestorNews*, nanoinvestornews.com, a site that posts news intended for Atomtech investors and maintains a database of companies involved in Atomtechnologies. NanotechInvestorNews features a "countries module," providing information about Atomtech activities organized by country. For access to some resources, registration is required, but there is no fee to register (September 2002). General and specific news related to Atomtechnologies is available from NanoApex at *news.nanoapex.com*, where readers can also post comments. There is a lot of overlap among NanoApex's three sites, but postings are frequent (several each day, in most cases) and the news is comprehensive.

www.nanobusiness.org

The NanoBusiness Alliance is a US-based trade group for the fledgling Atomtech industry. Created in mid-2001, it is scrambling for membership and struggling for recognition as the industry's lobbyist and media manager. The NanoBusiness Alliance states as its mission "to create a collective voice for advancing the small tech and nanotechnology industries, developing a range of initiatives to support the small tech business community." The Alliance's reports resulting from market research (and including patent surveys) run in the thousands of (US) dollars.

www.phantomsnet.com

The phantoms Network is funded by the European Commission and is focused on nanoelectronics development. As of September 2002, the Network was made up of 176 interdisciplinary research groups (government, university and industry) from 22 different European countries, along with a small number of groups from the usa, Canada, Japan and India. The phantoms web site posts international news related to nanoelectronics (follow the "nanonews" link under *general info*); it provides a summary of European research projects (follow the "European projects" link under *resources*) and links to eu companies, labs, research institutions and networks (follow the "useful links" link under *resources*). For more general information about European-based scientific research, go to the Community Research & Development Information Service's web site: *www.cordis.lu*. From the cordis home page, click on "Databases and Web Services" link to search over a dozen databases related to Europe's scientific research—including databases of projects, reports, eu official documents, even a dictionary of acronyms.

www.smalltimes.com

Small Times is "the first media company devoted entirely to the fast-growing industry that includes mems [microelectrical mechanical systems], microsystems, and nanotechnologies." It provides daily news coverage and searchable archives, including patent searches by keyword. Small Times promotes the development of Atomtechnologies. It is a useful resource for its comprehensive news. Small Times also publishes a bimonthly hard copy journal.

www.technologyreview.com

Technology Review is a journal published by the Massachusetts Institute of Technology that aims to promote "the understanding of emerging technology and its impact on the world." The journal focuses on "the process by which new technology gets out of the lab and into the marketplace." The articles assume a basic knowledge of Atomtech and can be scientifically in-depth, but are generally accessible to the lay reader. The web site does make available useful articles on nanotechnology research and development, but reserves a large portion of its content (including patent "scorecards" for universities and corporations) for paid subscribers.

APPENDIX B: NanoGrammar[1]

Assembler a chemical device that, given certain atomic or molecular starting materials, can produce a specific molecular structure. K. Eric Drexler believes that the work of **Molecular Manufacture** will be performed by assemblers.

Atom a particle of matter that uniquely defines a chemical element. It consists of a nucleus surrounded by one or more electrons. Each electron is negatively charged; the nucleus is positively charged, and contains particles known as protons and neutrons.

Atomic Force Microscope (AFM) is an example of **Scanning Probe Microscopy**. An afm allows interaction with matter on a very small scale, at the level of molecules. The tip of the afm is attached to the end of a highly sensitive cantilevered arm and touches the surface of the sample to be examined. The force of contact is very small. The afm records and measures the small upward and downward movements that are needed to maintain a constant force on the sample. The tip 'feels' the surface the way a finger might stroke a cheek. Because the touch must be delicate in order not to destroy the sample, several different methods have been developed, including one that gently taps the sample at unimaginably tiny intervals as it moves across its surface. The AFM followed the **Scanning Tunneling Microscope** and differs from it by making contact with the material rather than relying on an electrical current running between them, making it possible to see non-conducting materials at the nano-scale.

Buckyball full name is buckminsterfullerene (commonly called fullerene), named for the architect who invented the geodesic dome. Discovered in 1985 by Robert Curl, Harold Kroto, and Richard Smalley, buckyballs are made of sixty carbon atoms arranged like the hexagons and pentagons of a soccer ball (and not unlike a geodesic dome). Curl, Kroto and Smalley shared the Nobel Prize in Chemistry (1996) for their discovery. The buckyball is the precursor to the nanotube discovered in 1991 by Sumio Iijima.

Catalyst a substance able to perform catalysis, which is the acceleration of a chemical reaction by lowering the energy barrier. The strict definition of catalysis requires that the catalyst not be affected by the overall reaction.

Clean Room a space where the amount of airborne particles (from those of a visible size to those on the nano-scale) is vastly reduced from everyday levels and strictly monitored. The temperature and humidity in a clean room environment are also controlled to allow the construction and analysis of nano-scale structures and devices without interference from contamination.

Composite in general, refers to anything made up of disparate parts or elements. Nanocomposites are a new class of materials derived from the incorporation of nano-scale particles into **polymers**.

Dendrimer Chemistry Scientists are developing a wide range of strategies for the synthesis, characterization and applications of synthetic three-dimensional macromolecules called dendrimers (so named because the structures resemble a tree with branches [dendrons]). During the last decade, dendrimer chemistry has expanded dramatically. The development was driven by the practical applications of dendrimers in inkjet toners, in vitro diagnostics and mri contrast agents. The envisaged applications are wider-ranging, including use in the manufacture of advanced microelectronics and magnetic storage devices. The proven capability of dendrimers to host, either in the internal cavities or on the surface, smaller molecules that can be later released in a slow equilibrium makes dendrimers promising drug delivery agents, as well as slow delivery agents for perfumes and herbicides.

Gray Goo Eric Drexler introduced the term in his 1986 book *Engines of Creation: The Coming Era of Nanotechnology*. Gray Goo refers to the obliteration of life that could result from the accidental and uncontrollable spread of self-replicating assemblers. Bill Joy and others have cautioned that the self-replicating miniature robots, though invisible to the human eye, could result in a kind of Gray Goo if their multiplication ever got out of control. Armies of "blue goo," or destructive nanomachines, have even been proposed as a law enforcement measure.

Informatics the software tools that allow scientists to capture, organize and analyze information data.

MicroElectroMechanical Systems (MEMS) integrated mechanical elements on a common silicon substrate. mems is a relatively new technology that exploits the existing microelectronics infrastructure to create complex machines with micron-sized feature sizes (a micron is 1000 nm). These machines have many applications, including sensing and communication.

Micron a measurement equal to one thousand nanometers.

Molecular Manufacturing/Molecular Nanotechnology method of creating products by means of molecular machinery, allowing molecule-by-molecule control of products and by-products through positional chemical synthesis.

Molecule a collection of atoms held together by strong bonds. It usually refers to a particle with a number of atoms small enough to be counted (a few to a few thousand).

Nano from the Greek "nanos" meaning dwarf; destined to become one of the most popular (and over-used) prefixes of the 21st century. Nano implies the scale of the nanometer, one billionth of a meter.

Nanometer (nm) a measurement equal to one billionth of a meter.

Nanoparticle a small piece of matter, composed of an individual element or a simple compound of elements, typically less than 100 nanometers in diameter. The term can refer to a wide range of materials, including the particulate matter that is expelled as car exhaust. In this document we refer to an industry that has been developing over the last decade to manufacture a range of particles, all on the nano-scale, that exhibit desirable properties. A compound created through traditional chemistry will have one set of properties. If that same compound is engineered to form nanoparticles, it may exhibit enhanced capabilities or even brand new properties. Nanoparticles can be manufactured, in the case of compounds, by vaporizing a solid, adding a reactive gas and cooling the vaporized molecules, which condense into nanoparticles. Pure metal nanoparticles can be also be made by evaporation-condensation techniques, but more creative methods, such as extracting the nano-scale gold that has been taken up by alfalfa plants, are being developed.

Nanotube cylinder-shaped molecule resembling rolled-up chicken wire. Nanotubes can be made of different substances, but most nanotube research focuses on tubes of pure carbon atoms. Carbon nanotubes are 100 times stronger than steel, impervious to temperatures up to 6,500 degrees Fahrenheit and only one to a few nanometers in width. Carbon nanotubes can be good conductors of electricity and heat. If a carbon nanotube is rolled up evenly, like a sheet of paper with the top and bottom edges lined up, it acts like a metallic conductor, efficiently carrying electricity. If a carbon nanotube is rolled up askew, like a mis-buttoned shirt, then its electrical properties change to those of a silicon-like semiconductor where current can be switched on and off. A transistor requires semiconducting nanotubes. (Kenneth Chang, *New York Times*, 3/27/01).

Polymer a substance, either natural or artificial, consisting of long-chain molecules, derived either by the addition of many smaller molecules or by the condensation of many smaller molecules with the elimination of water, alcohol, or the like. Plastic is the most well-known artificial polymer.

Quantum Dot is a nano-scale particle (a few hundred to a few thousand atoms) with extraordinary optical properties that can be customized by changing the size or composition of the particle. Quantum dots absorb light, then quickly re-emit the light but in a different colour, which can be "tuned" to any chosen wavelength simply by changing the size of the dots, useful for biological labeling in diagnostics and drug development.

Quantum Mechanics a system of mechanics based on quantum theory that explains phenomena observable at the atomic level (<50 nm), phenomena that differ from those observable on larger scales.

Quantum Modeling computer simulations that allow researchers to predict how materials will perform at the nano-scale, governed by the laws of quantum mechanics.

Periodic Table a complete list of all known chemical elements (approximately 115, at present) arranged in columns and rows according to chemical properties. Russian chemist Dimitri Mendeleyev produced the first list in 1869. Mendeleyev's list proposed about 60 elements.

Replicator a system able to build copies of itself when raw materials and energy are provided.

Scanning Probe Microscopy a general term that refers to scanning a needle-like tip across the surface of a sample in order to create a graphic image of the sample's contours.

Scanning Tunneling Microscope an stm brings a sharp, electrically conducting needle-like tip up to an electrically conducting surface, almost touching it. The tip and the surface are electrically connected so that a current will flow if they touch, like closing a switch. A detectable current flows when just two atoms are in tenuous contact, one on the surface and one on the tip of the needle. By delicately maneuvering the needle over the surface, keeping the current flowing at a tiny, constant rate, the stm can map the contours of the surface with great precision. The stm was developed in an ibm research lab, Zurich, Switzerland, throughout the 70s and 80s and can be used to "pick up" and relocate atoms. If the voltage is increased when the needle is placed exactly over an atom, then the atom will stick to the needle tip; the atom can be moved and positioned while stuck to the needle tip, the voltage lowered and the atom released from the tip and put in the desired spot (K. Eric Drexler, *Unbounding the Future*, pp. 92-94).

Self-Assembly A method of integration in which the components spontaneously assemble, typically by bouncing around in a solution or gas phase until a stable structure of minimum energy is reached. Components in self-assembled structures find their appropriate location based solely on their structural properties (or chemical properties in the case of atomic or molecular self-assembly), with an energy difference between the starting and finished state being the driving force.

Supramolecule A system of two or more molecular entities held together and organized by means of intermolecular binding interactions.

Table of Elements See Periodic Table.

Notes

1 Adapted from glossaries available on the Internet and from K. Eric Drexler's *Unbounding the Future*, as well as other sources cited within the definitions.

The ETC Group:
The Action Group on Erosion, Technology and Concentration
www.etcgroup.org

The etc Group (formerly known as rafi) is an international civil society organization based in Winnipeg, Canada. etc Group (pronounced et cetera Group) is dedicated to the conservation and sustainable advancement of cultural and ecological diversity and human rights. To this end, etc Group supports socially responsible developments in technologies useful to the poor and marginalized and it addresses governance issues affecting the international community. We also monitor the ownership and control of technologies, and the consolidation of corporate power.

Since the 1970s, etc Group (as rafi until 2001) has conducted groundbreaking research, education and social action campaigns on issues involving agricultural biodiversity, intellectual property and community knowledge systems. We have been active critics of intellectual property (patents), especially with respect to living materials. In the 1980s and 1990s, our work expanded to encompass concerns related to biotechnology, biopiracy, human genomics and a set of new technologies known as nanotechnologies.

The combined themes of **Erosion** (cultural and environmental); **Technology** (as it transforms society); and **Concentration** (of corporate power) form the operating framework for etc Group's research and programme of work.

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etc Group conducted these workshops and prepared this report as part of its contribution to the policy work of the cbdc [Community Biodiversity Development and Conservation Programme].

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"But I am not afraid
to consider the final
question as to whether,
ultimately—in the great
future—we can arrange
the atoms the way we
want; the very atoms,
all the way down!"

Richard Feynman
"There's Plenty of Room at the Bottom," 1959

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